# Neutrinos and Solar Metalicity

- The solar abundance problem and CN neutrinos
- Measurement opportunities

Wick Haxton INT 8 June 2015

# The Standard Solar Model

- ❑ Origin of solar neutrino physics: desire to test a model of low-mass, main-sequence stellar evolution
  - local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - hydrogen burning: pp chain, CN cycle
  - energy transport by radiation (interior) and convection (envelope)
  - boundary conditions: today's mass, radius, luminosity

- ❑ The implementation of this physics requires
  - electron gas EOS
  - low-energy nuclear cross sections
  - radiative opacity
  - some means of fixing the composition at ZAMS, including the ratios X:Y:Z

## Composition/metallicity in the SSM:

- ❑ Standard picture of pre-solar contraction, evolution
  - – Sun forms from a contracting primordial gas cloud
  - – passes through the Hayashi phase: cool, highly opaque, large temperature gradients, slowly contracting ↔ convective (mixed)
  - – radiative transport becomes more efficient at star's center: radiative core grows from the center outward
  - – when dense and hot enough, nuclear burning starts...

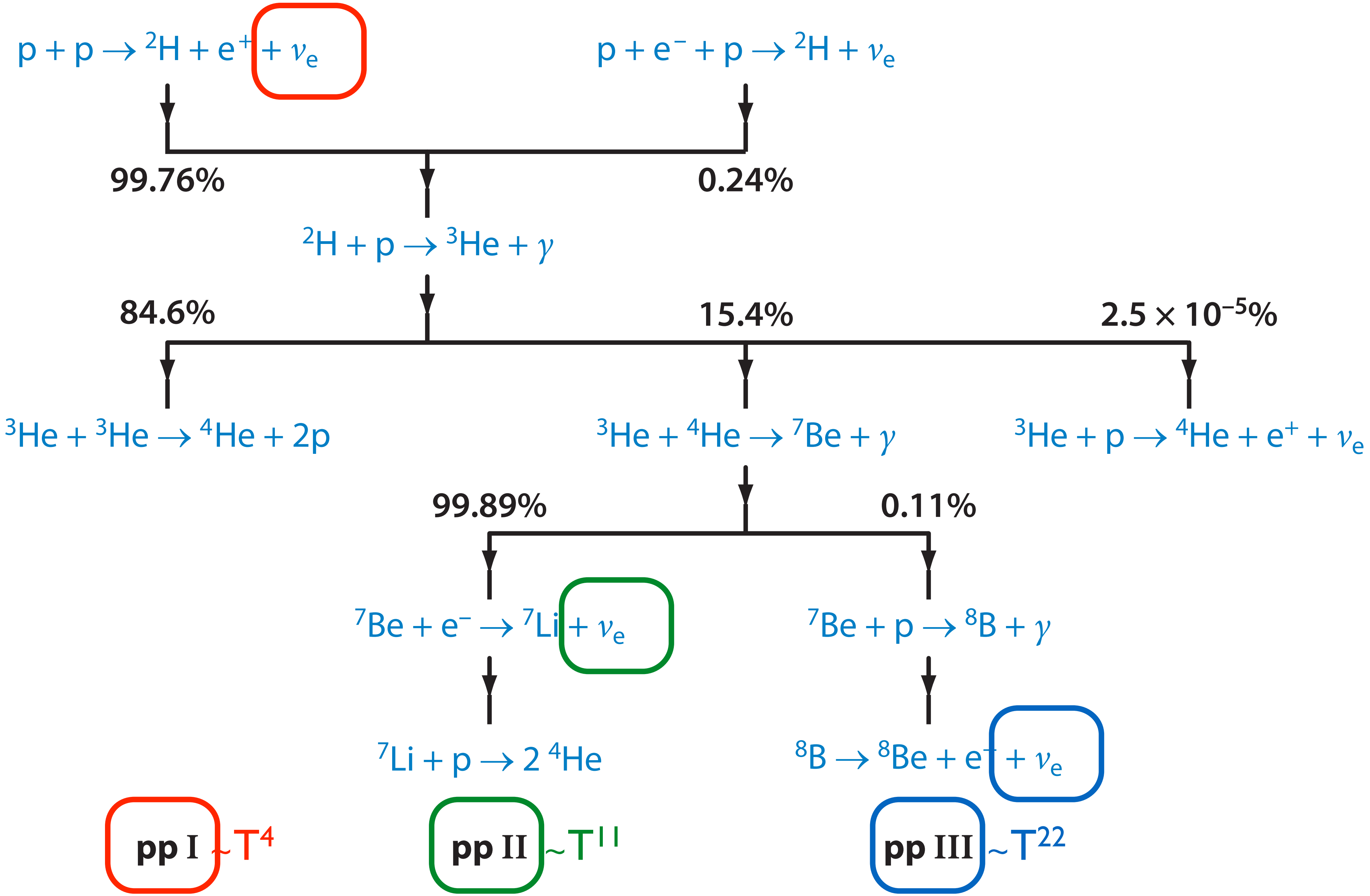
- ❑ Because the Hayashi phase fully mixes the proto-Sun, a chemically homogeneous composition is traditionally assumed at ZAMS
  - – $X_{ini} + Y_{ini} + Z_{ini} = 1$
  - – relative metal abundances taken from a combination of photospheric (volatile) and meteoritic (refractory) abundances
  - – $Z_{ini}$ fixed by model's present-day $Z_S$, corrected for diffusion
  - – $Y_{ini}$ and $\alpha_{MLT}$ adjusted to produce present-day $L_\odot$ and $R_\odot$

## Model tests:

- ❏ Solar neutrinos: direct measure of core temperature to ~ 0.5%
  - − once the flavor physics has been sorted out

- ❏ Helioseismology: inversions map out the local sound speed, properties of the convective zone

$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$\mathrm{p} + e^- + \mathrm{p} \rightarrow {}^2\mathrm{H} + \nu_e$

99.76%

0.24%

${}^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$

84.6%

15.4%

$2.5 \times 10^{-5}\%$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

99.89%

0.11%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$

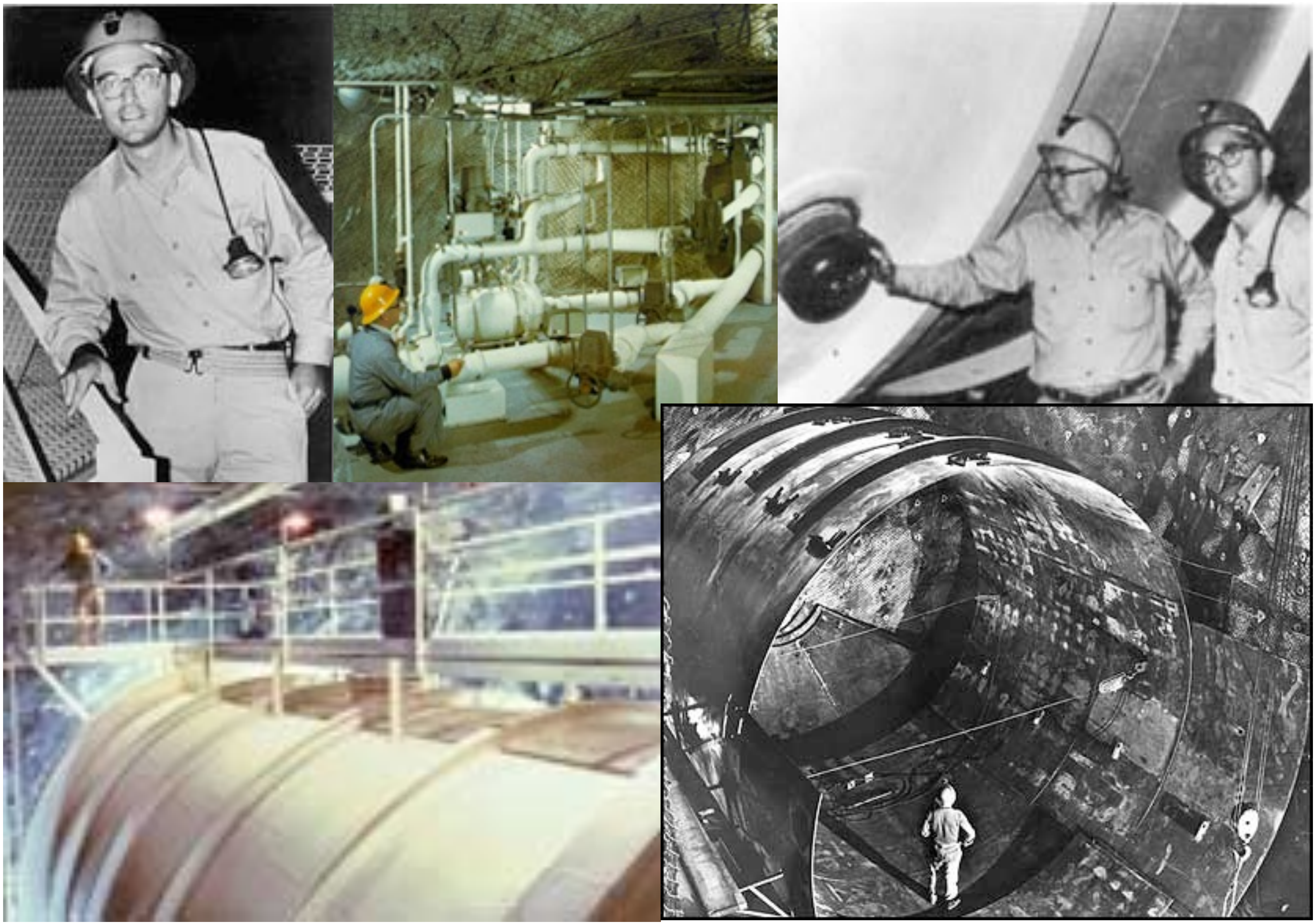
${}^7\mathrm{Li} + \mathrm{p} \rightarrow 2\ {}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

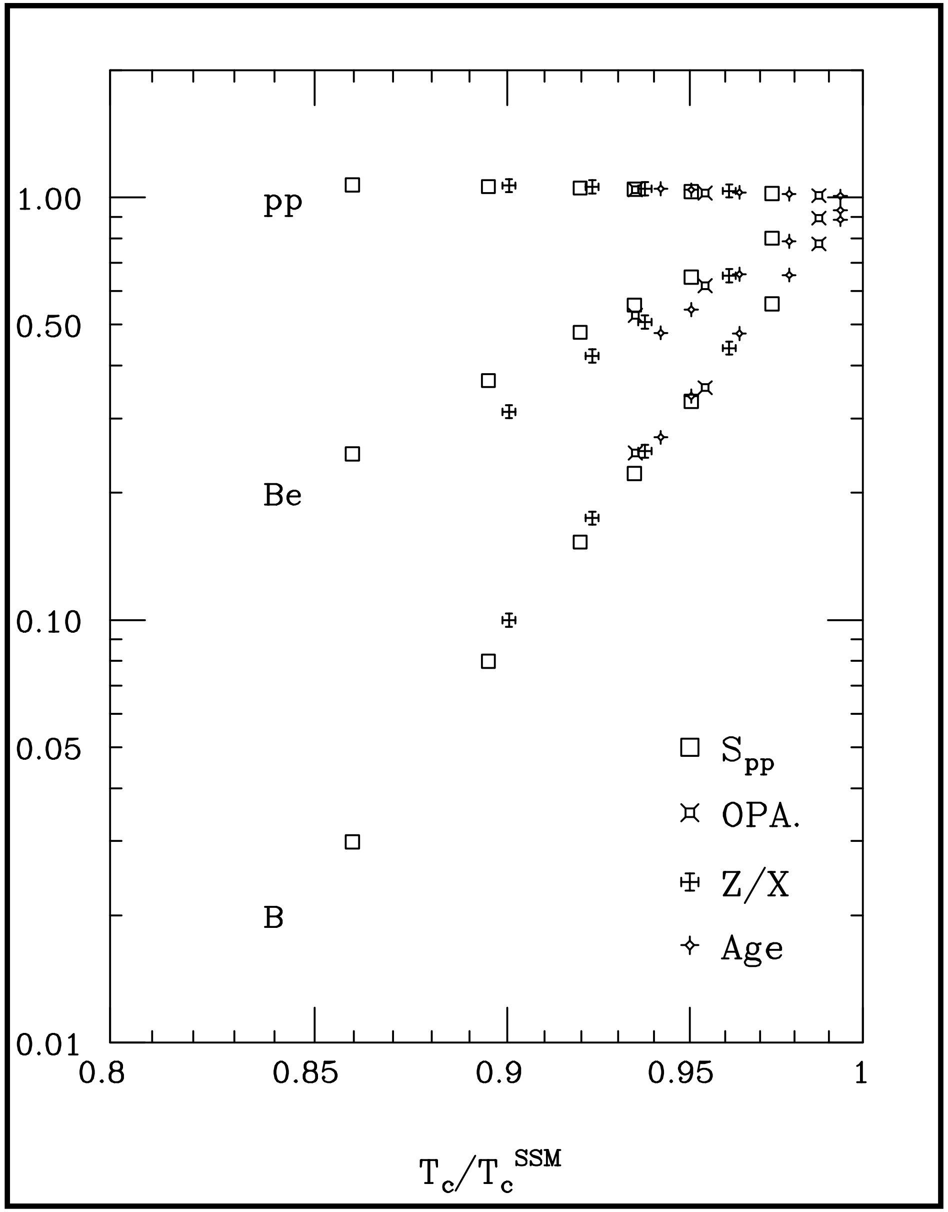
**pp I** $\sim T^4$

**pp II** $\sim T^{11}$

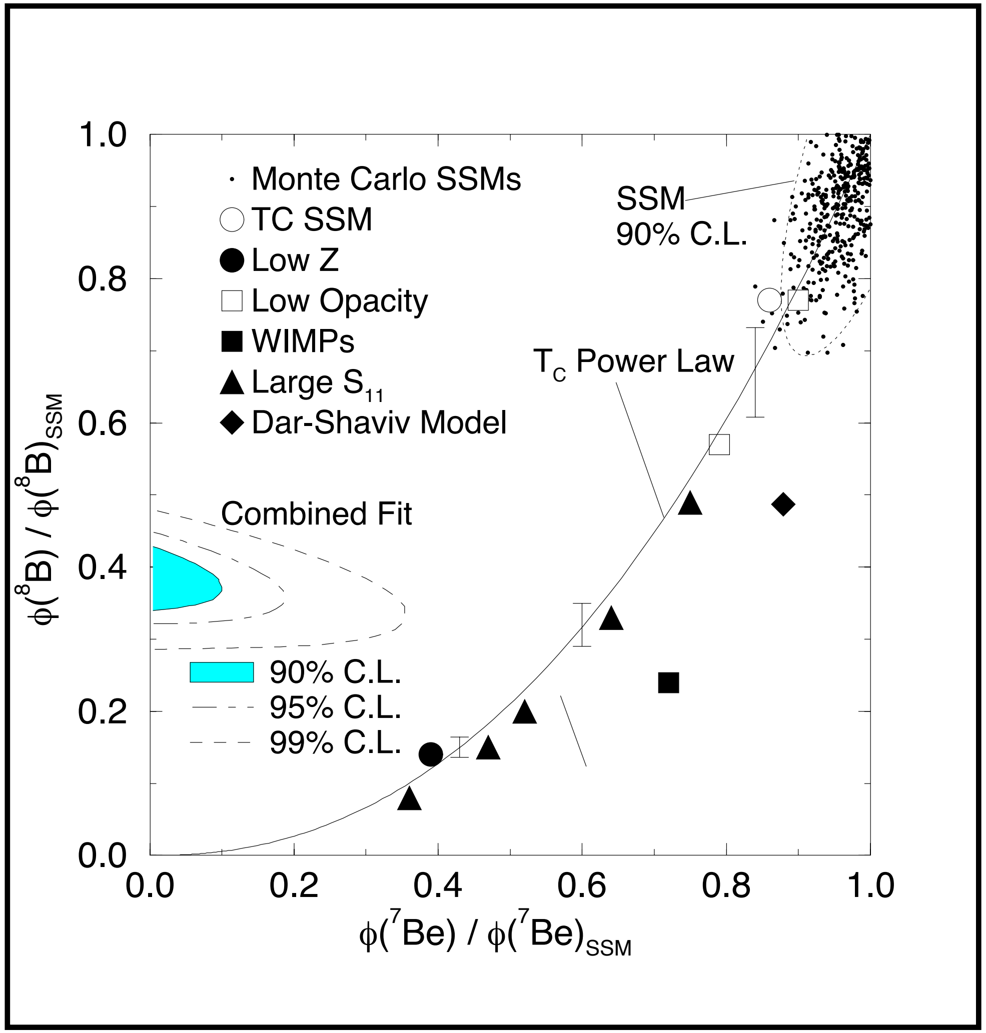
**pp III** $\sim T^{22}$



# By mid-1990s model-independent arguments developed showing that no adjustment in the SSM could reproduce observed $\nu$ fluxes (Cl, Ga, water exps.)

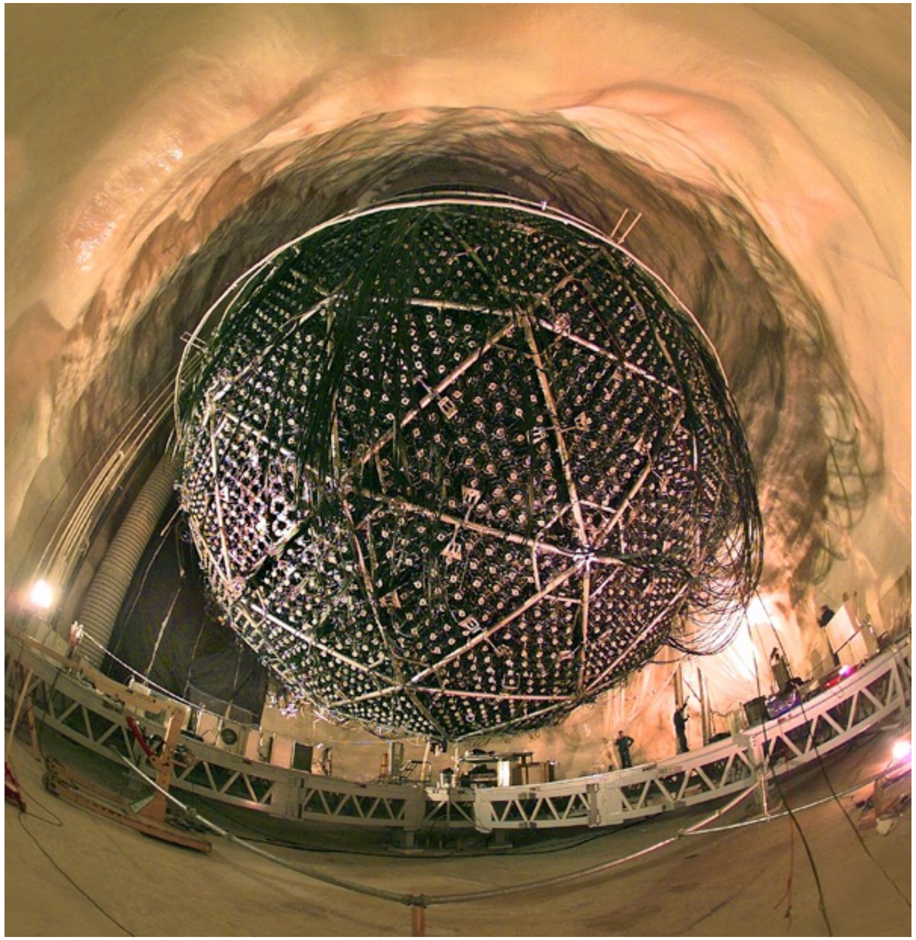


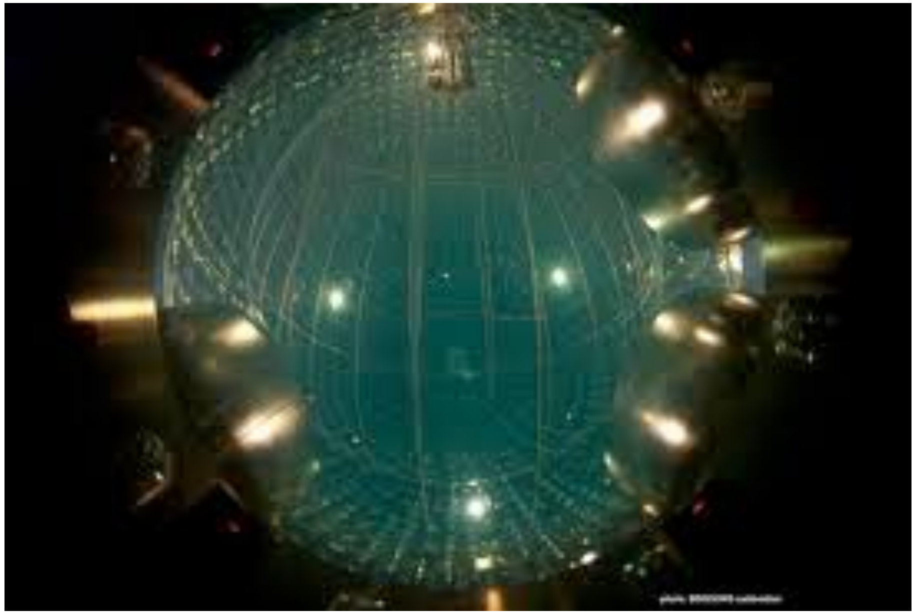
Castellani et al.

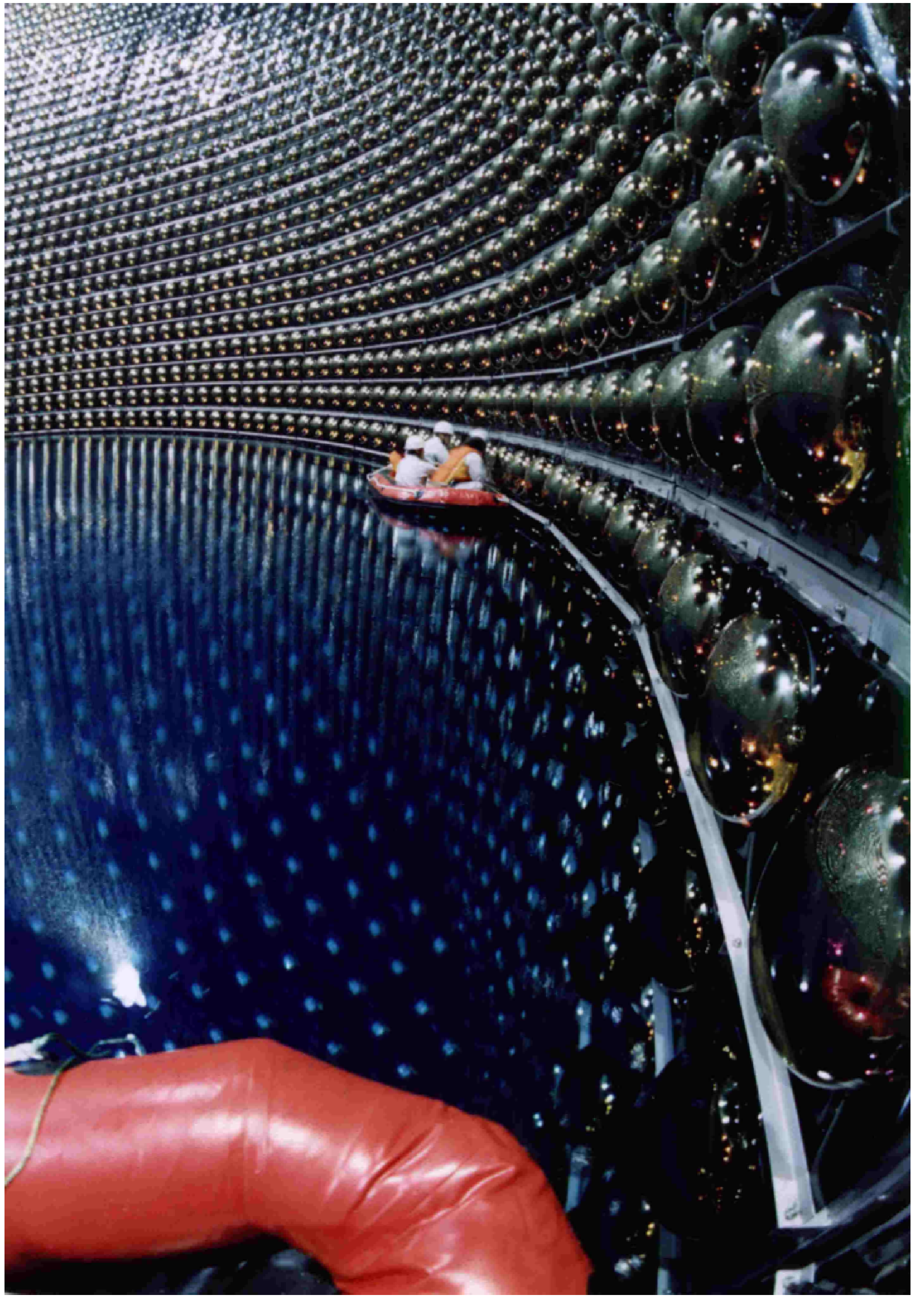


Hata et al.

(and Heeger and Robertson )



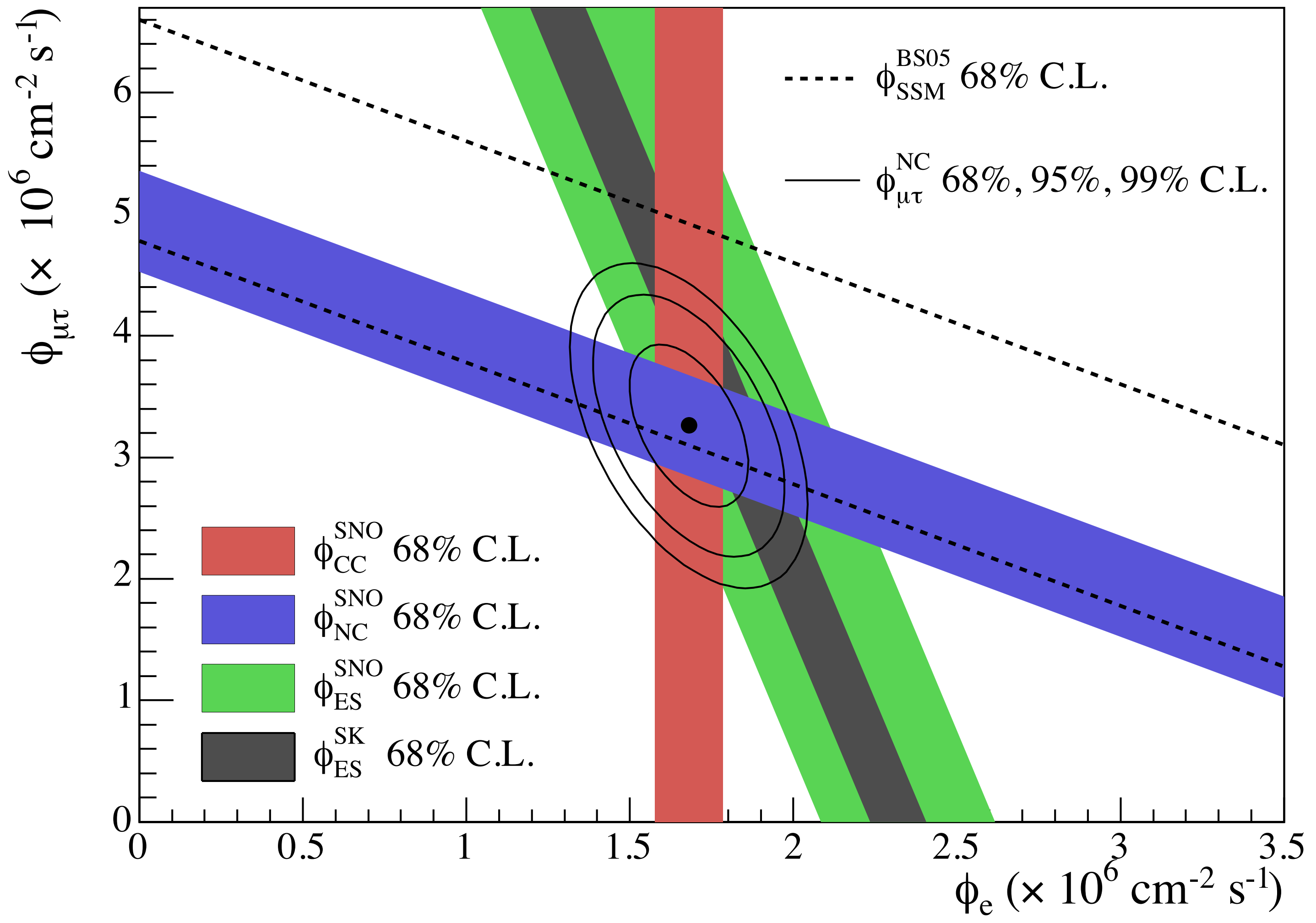




SNO, Super-Kamiokande, Borexino

the “solar $\nu$ problem” was definitively traced to new physics by SNO

flavor conversion $\nu_e \rightarrow \nu_{heavy}$



requires an extension of the SM -- Majorana masses or $\nu_R$

| | | high-Z SSM | low-Z SSM | luminosity constrained fit to data | |
|---|---|---|---|---|---|
| $\nu$ flux | $E_\nu^{\max}$ (MeV) | GS98-SFII | AGSS09-SFII | Solar | units |
| $p+p\rightarrow{}^2H+e^++\nu$ | 0.42 | $5.98(1 \pm 0.006)$ | $6.03(1 \pm 0.006)$ | $6.05(1^{+0.003}_{-0.011})$ | $10^{10}/cm^2s$ |
| $p+e^-+p\rightarrow{}^2H+\nu$ | 1.44 | $1.44(1 \pm 0.012)$ | $1.47(1 \pm 0.012)$ | $1.46(1^{+0.010}_{-0.014})$ | $10^8/cm^2s$ |
| ${}^7Be+e^-\rightarrow{}^7Li+\nu$ | 0.86 (90%) | $5.00(1 \pm 0.07)$ | $4.56(1 \pm 0.07)$ | $4.82(1^{+0.05}_{-0.04})$ | $10^9/cm^2s$ |
| | 0.38 (10%) | | | | |
| ${}^8B\rightarrow{}^8Be+e^++\nu$ | $\sim 15$ | $5.58(1 \pm 0.14)$ | $4.59(1 \pm 0.14)$ | $5.00(1 \pm 0.03)$ | $10^6/cm^2s$ |
| ${}^3He+p\rightarrow{}^4He+e^++\nu$ | 18.77 | $8.04(1 \pm 0.30)$ | $8.31(1 \pm 0.30)$ | — | $10^3/cm^2s$ |
| ${}^{13}N\rightarrow{}^{13}C+e^++\nu$ | 1.20 | $2.96(1 \pm 0.14)$ | $2.17(1 \pm 0.14)$ | $\leq 6.7$ | $10^8/cm^2s$ |
| ${}^{15}O\rightarrow{}^{15}N+e^++\nu$ | 1.73 | $2.23(1 \pm 0.15)$ | $1.56(1 \pm 0.15)$ | $\leq 3.2$ | $10^8/cm^2s$ |
| ${}^{17}F\rightarrow{}^{17}0+e^++\nu$ | 1.74 | $5.52(1 \pm 0.17)$ | $3.40(1 \pm 0.16)$ | $\leq 59.$ | $10^6/cm^2s$ |
| $\chi^2/P^{agr}$ | | 3.5/90% | 3.4/90% | | |

With the new ν physics added, theory and experiment seem to coincide

## Recent Re-evaluations of Photospheric Abundances

❑ SSM requires as input an estimate of core metalicity at t=0, an assumes a homogeneous zero-age Sun

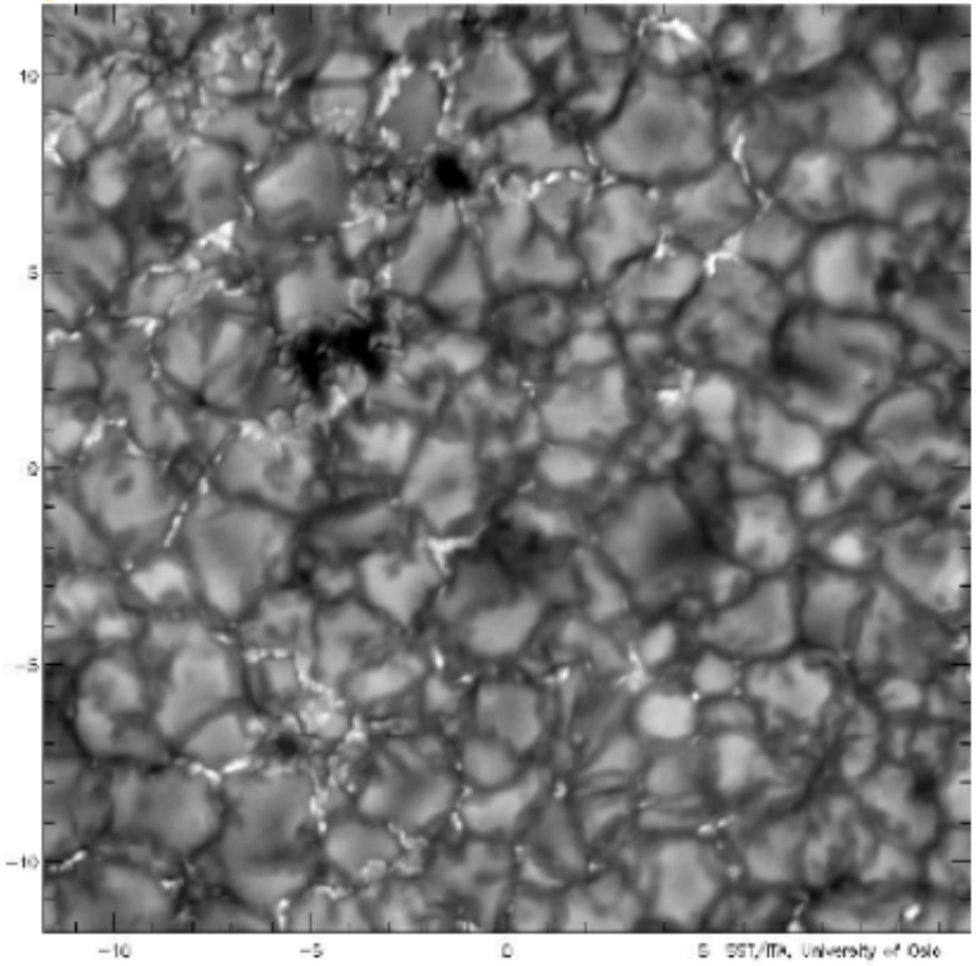
❑ The metals have an important influence on solar properties: free-bound transitions important to opacity, influencing local sound speed

❑ The once excellent agreement between SSM and helioseismology due in part to this input (Grevesse & Sauval 1998)

- The classic analyses modeled the photosphere in 1D, without explicit treatments of stratification, velocities, inhomogenieties

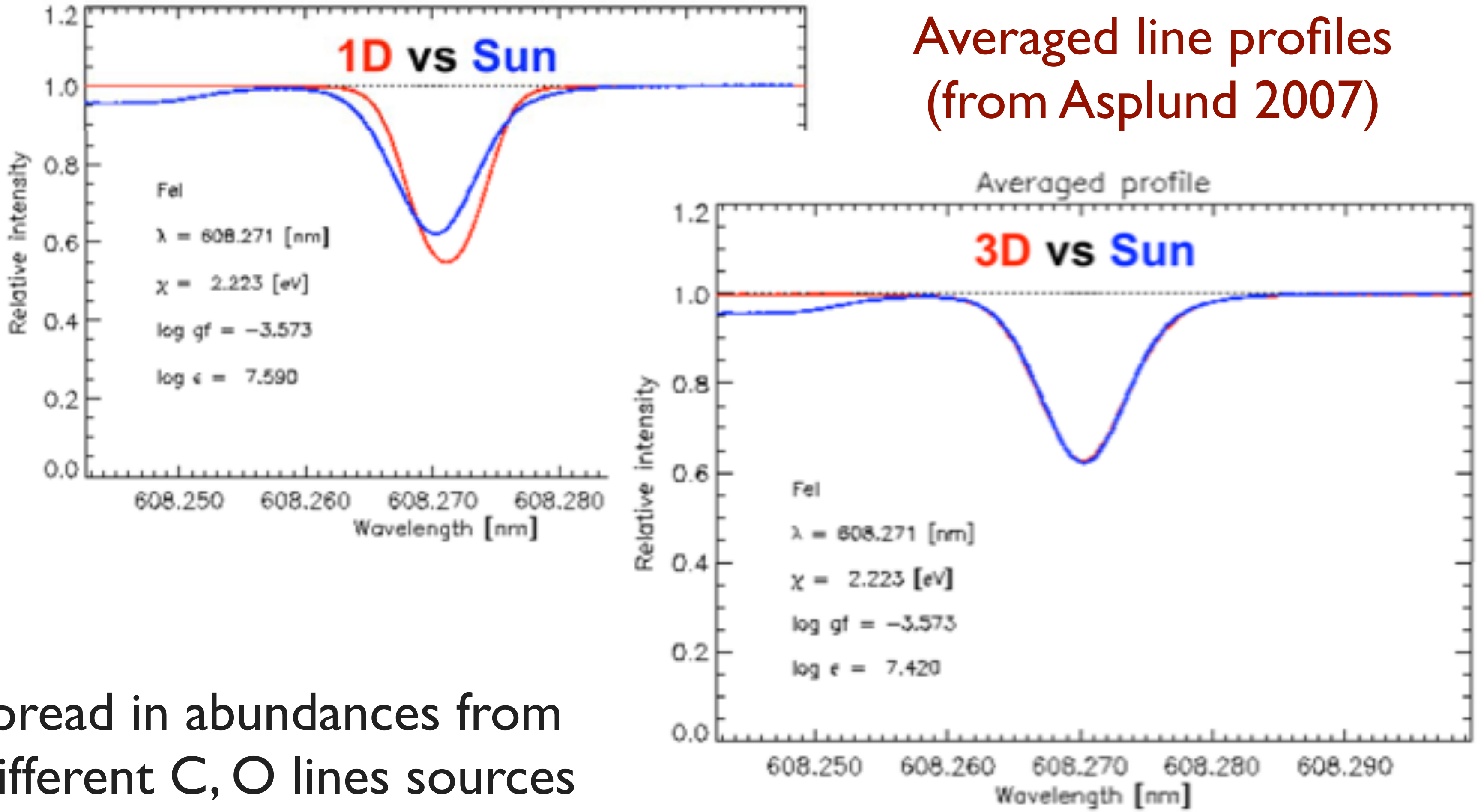
- New 3D, parameter-free methods were then introduced, significantly improving consistency of line analyses:  MPI-Munich

Dynamic and 3D due to convection



Mats Carlsson (Oslo)

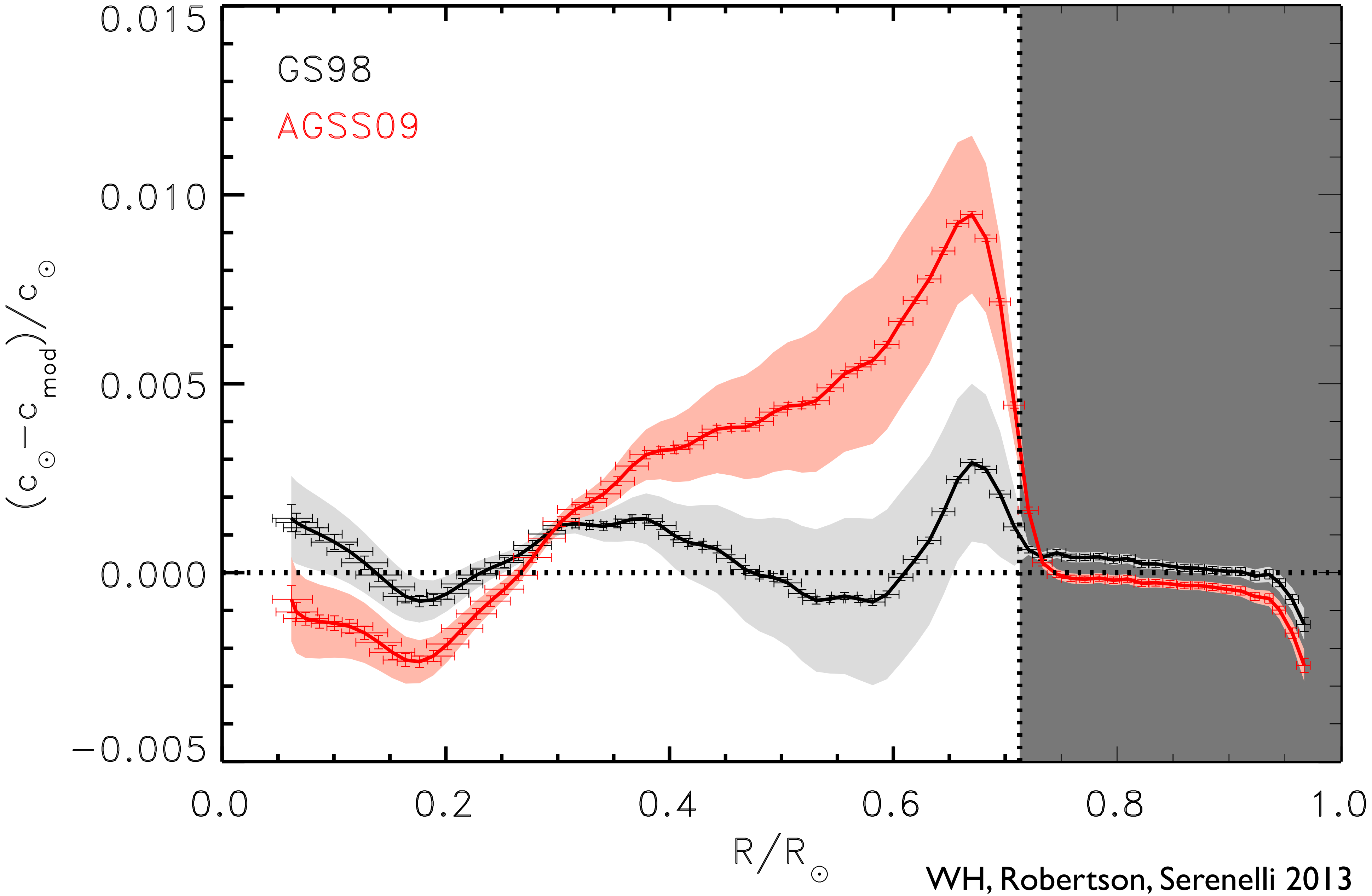
Sun



Averaged line profiles
(from Asplund 2007)

- ❑ Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- ❑ But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- ❑ Makes sun more consistent with similar stars in local neighborhood
- ❑ Lowers SSM $^8$B flux by 20%

# But adverse consequences for helioseismology



WH, Robertson, Serenelli 2013

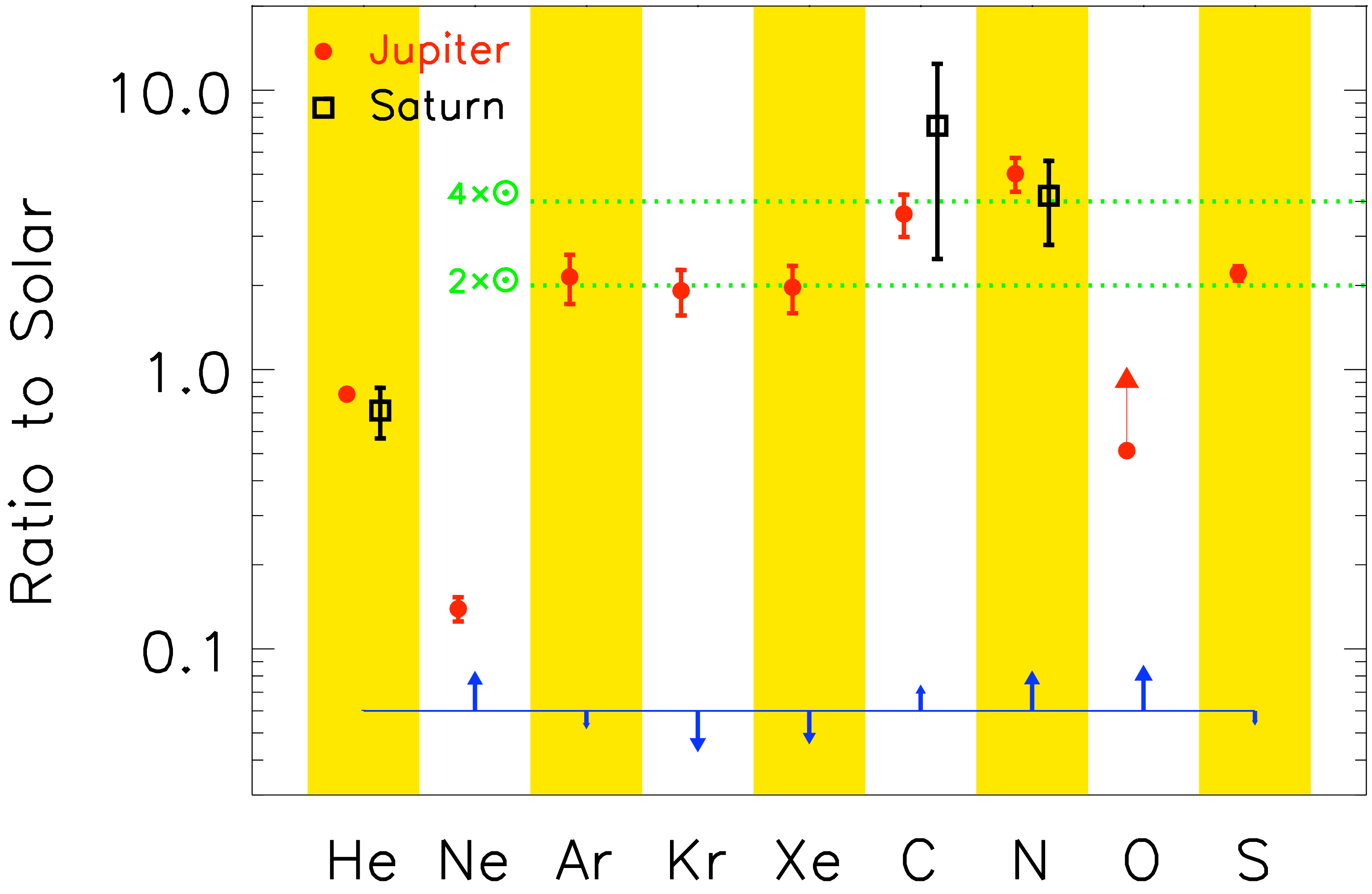
**Table 1** **Standard solar model characteristics are compared to helioseismic values, as determined by Basu & Antia (1997, 2004)**

| Property[a] | GS98-SFII | AGSS09-SFII | Solar |
|---|---|---|---|
| $(Z/X)_S$ | 0.0229 | 0.0178 | – |
| $Z_S$ | 0.0170 | 0.0134 | – |
| $Y_S$ | 0.2429 | 0.2319 | 0.2485 ± 0.0035 |
| $R_{CZ}/R_\odot$ | 0.7124 | 0.7231 | 0.713 ± 0.001 |
| $\langle \delta c/c \rangle$ | 0.0009 | 0.0037 | 0.0 |
| $Z_C$ | 0.0200 | 0.0159 | – |
| $Y_C$ | 0.6333 | 0.6222 | – |
| $Z_{ini}$ | 0.0187 | 0.0149 | – |
| $Y_{ini}$ | 0.2724 | 0.2620 | – |

Solar abundance problem: A disagreement between SSMs that are optimized to agree with interior properties deduced from our best analyses of helioseismology (high Z), and those optimized to agree with surface properties deduced from the most complete 3D analyses of photoabsorption lines (low Z).

Difference is ~ 40 $M_{\oplus}$ of metal, when integrated over the Sun's convective zone ( which contains about 2.6% of the Sun's mass)

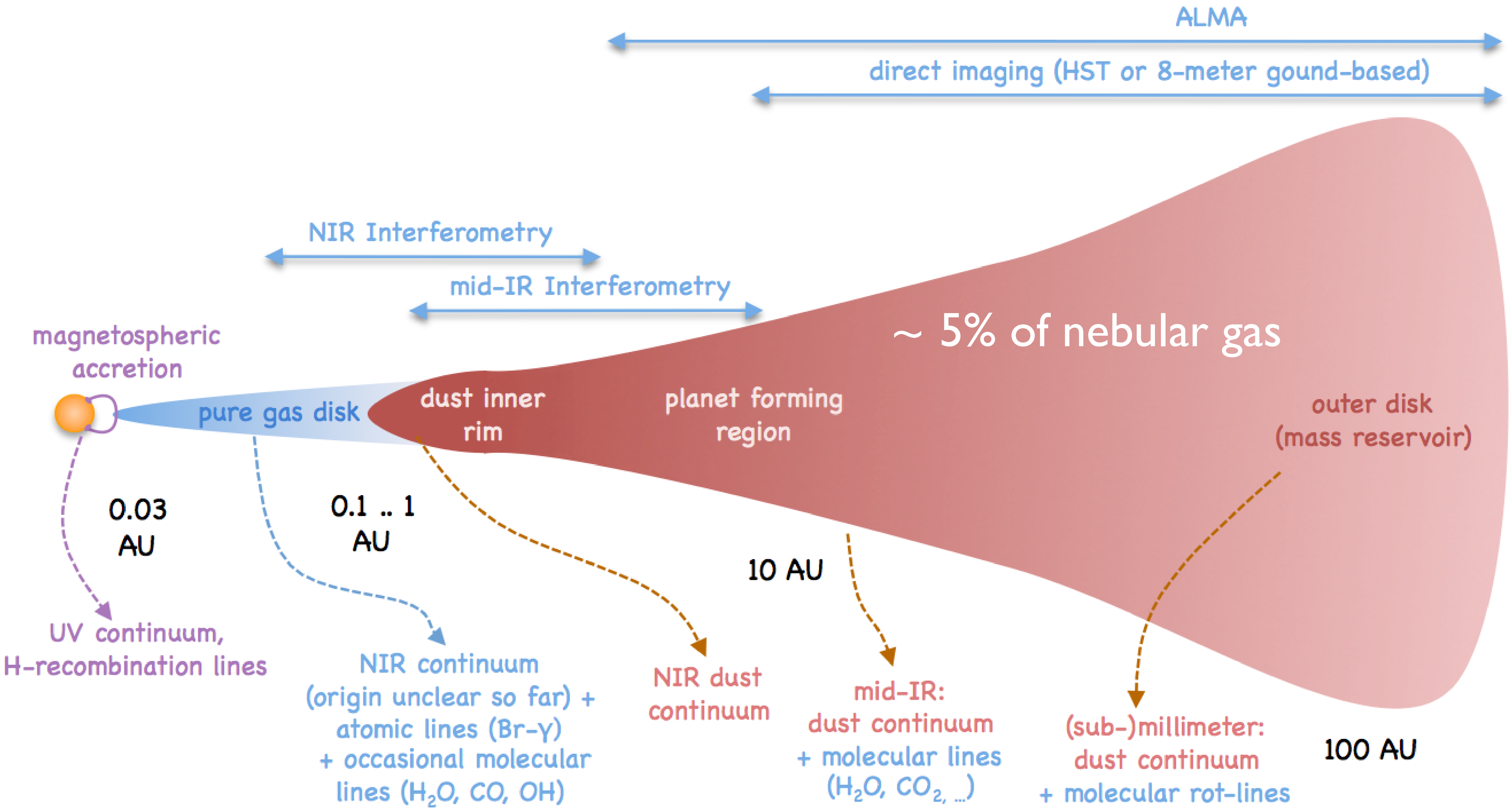
# Did the Sun form from a homogeneous gas cloud?



Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

# Contemporary picture of metal segregation, accretion



ALMA

direct imaging (HST or 8-meter gound-based)

NIR Interferometry

mid-IR Interferometry

magnetospheric accretion

pure gas disk

dust inner rim

planet forming region

~ 5% of nebular gas

outer disk (mass reservoir)

0.03 AU

0.1 .. 1 AU

10 AU

100 AU

UV continuum,
H-recombination lines

NIR continuum
(origin unclear so far) +
atomic lines (Br-γ)
+ occasional molecular
lines ($H_2O$, CO, OH)

NIR dust
continuum

mid-IR:
dust continuum
+ molecular lines
($H_2O$, $CO_2$, ...)

(sub-)millimeter:
dust continuum
+ molecular rot-lines

Dullemond and Monnier, ARA&A 2010

This (removal of ice, dust) from gas stream could alter Sun if

- processed gas - from which the elements we see concentrated in Jupiter were scrubbed - remains in the solar system, not expelled
- the Sun had a well-developed radiative core at the time of planetary formation (thus an isolated convective zone)

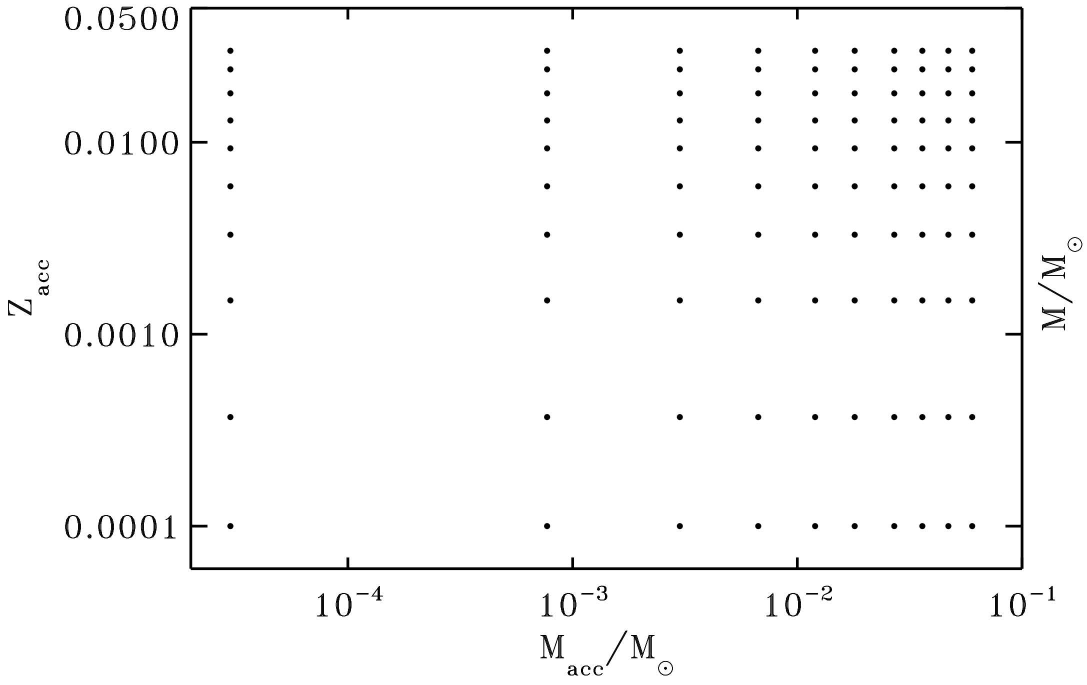
Numerically the mass of metals extracted by the protoplanetary disk is more than sufficient to account for the needed dilution of the convective zone (40-90 $M_\oplus$)

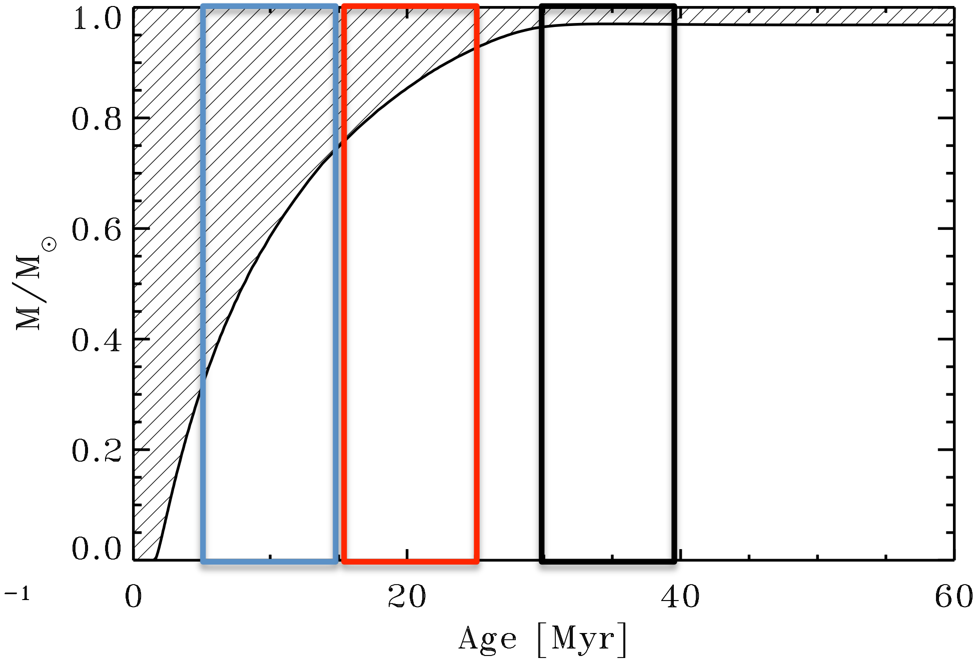
Guzik, vol. 624, ESA (2006) 17
Castro, Vauclair, Richard A&A 463 (2007) 755
WH & Serenelli, Ap. J. 687 (2008) 678
Nordlund (2009) arXiv:0908.3479
Guzik and Mussack, Ap. J. 713 (2010) 1108
Serenelli, WH, Pena-Garay, Ap. J. 743 (2011) 24

# Self-consistent accreting nonstandard SMs

Evolve models with accretion in which the AGSS09 surface composition is taken as a constraint, Z is varied, but H/He is assumed fixed

*Serenelli, Haxton, Peña-Garay 2011*

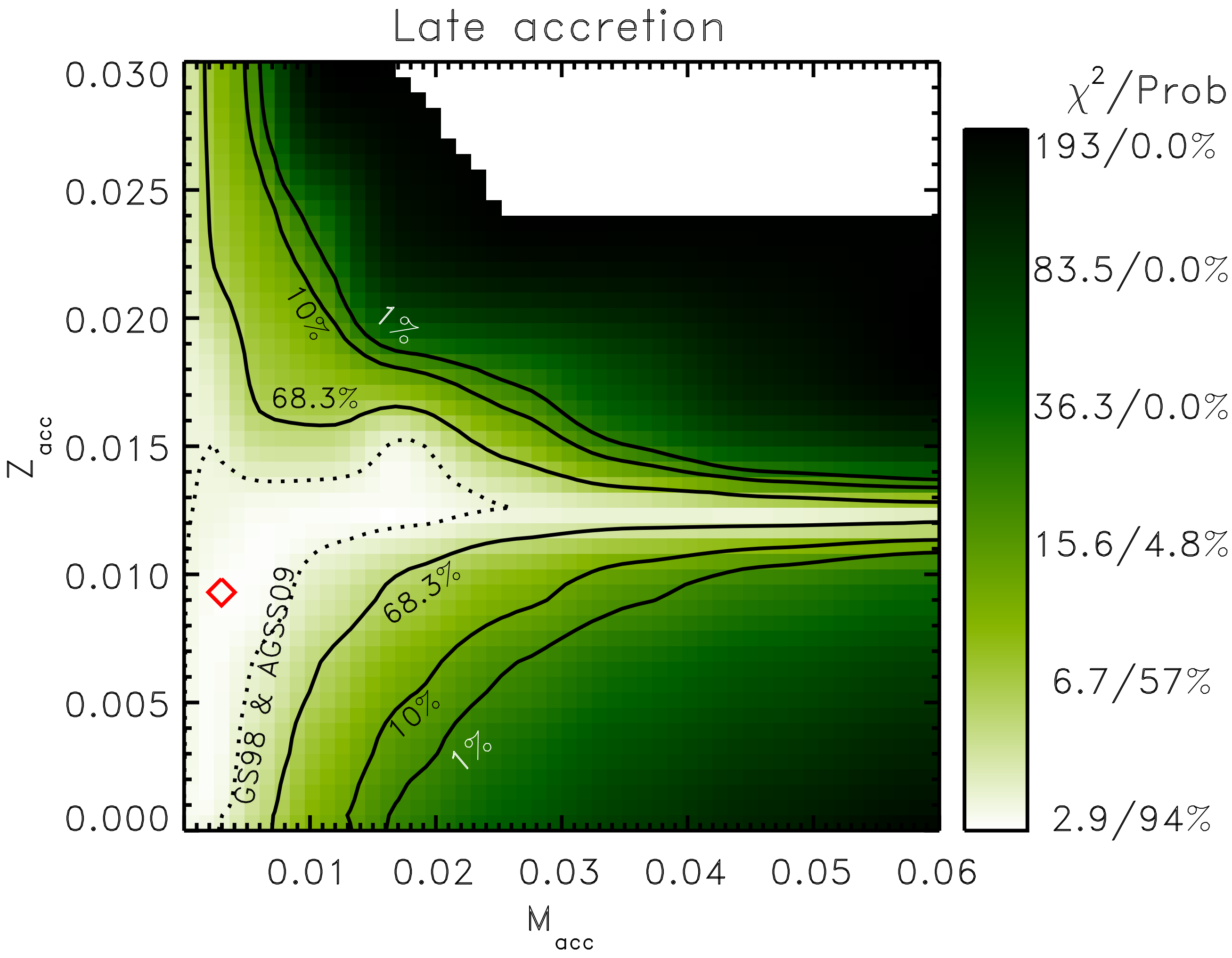




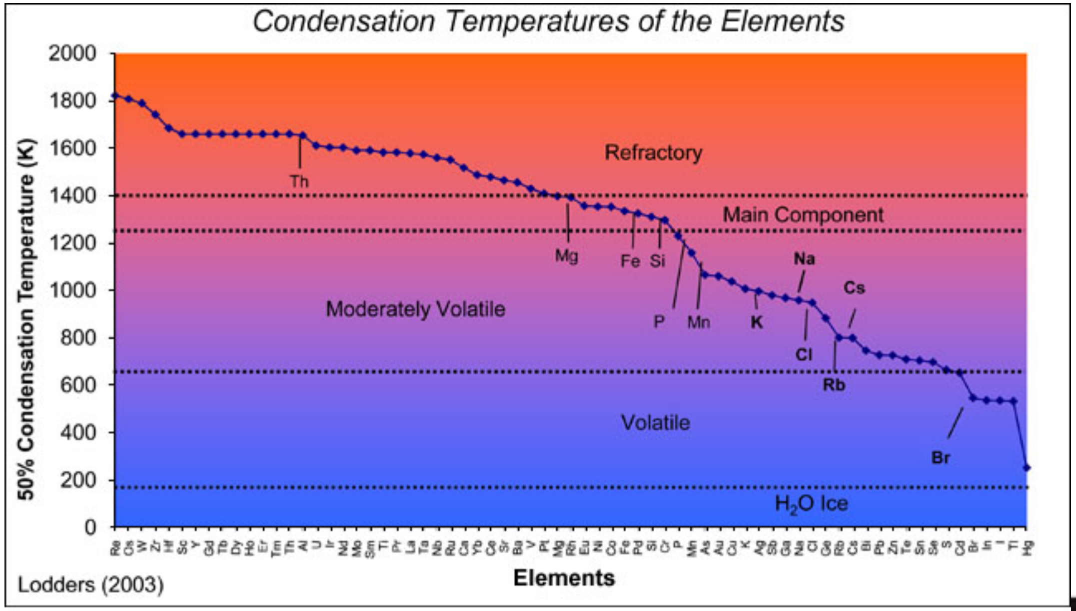
$M_{accr} < 0.06\ M_{solar}$
$0 < Z_{accr} < 0.03\ (2\ Z_{solar})$

$t_{accr} = 5, 15, 30$ Myr
($M_{conv}(t_{accr})$ determines dilution)
$\Delta t_{accr} < 10$ Myr

# neutrino constraints



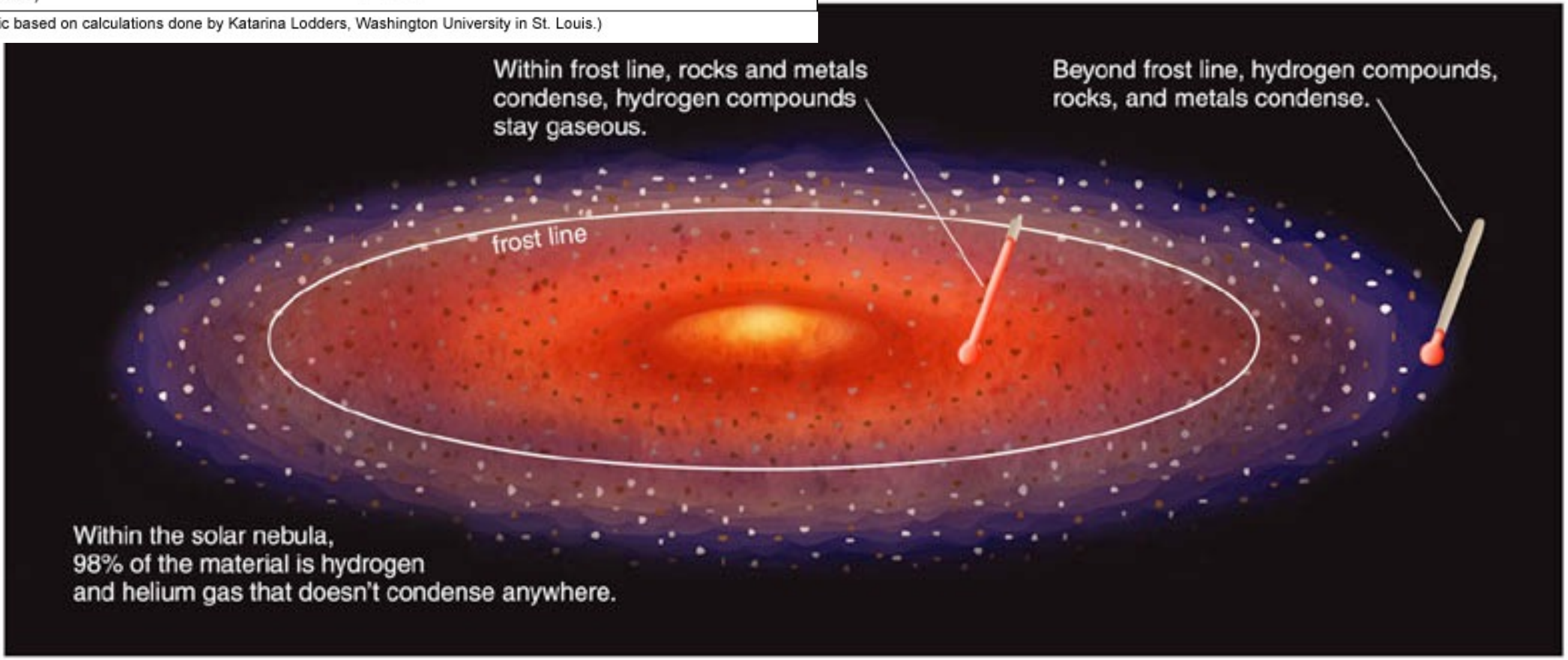
For measured neutrino fluxes restrict accretion scenarios largely to those with modest masses of low-Z material



(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)

modeling done to date is
somewhat naive:
expect in condensation,
refractory > volatile > He

*refractory elements condense*



Within frost line, rocks and metals condense, hydrogen compounds stay gaseous.

Beyond frost line, hydrogen compounds, rocks, and metals condense.

Within the solar nebula, 98% of the material is hydrogen and helium gas that doesn't condense anywhere.

$H_2O$ condenses

# Abundances in solar twins

- Differential measurements of abundances in "solar twins" lacking Jupiters:

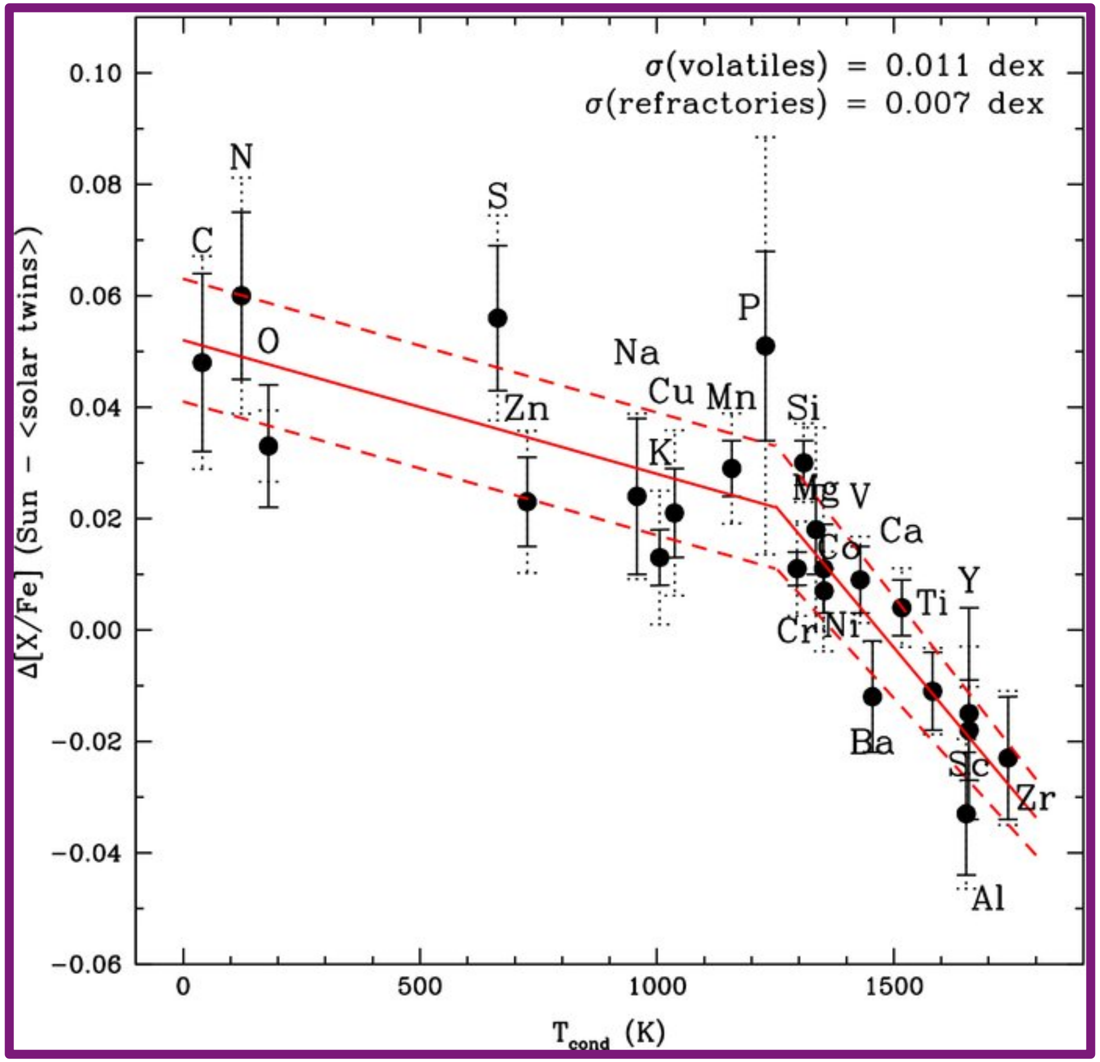
  *Melendez et al. 2009*
  *Ramirez et al. 2010*

- Claim: solar ratio of volatiles/ refractories is higher than twin ratio by 0.05-0.10 dex

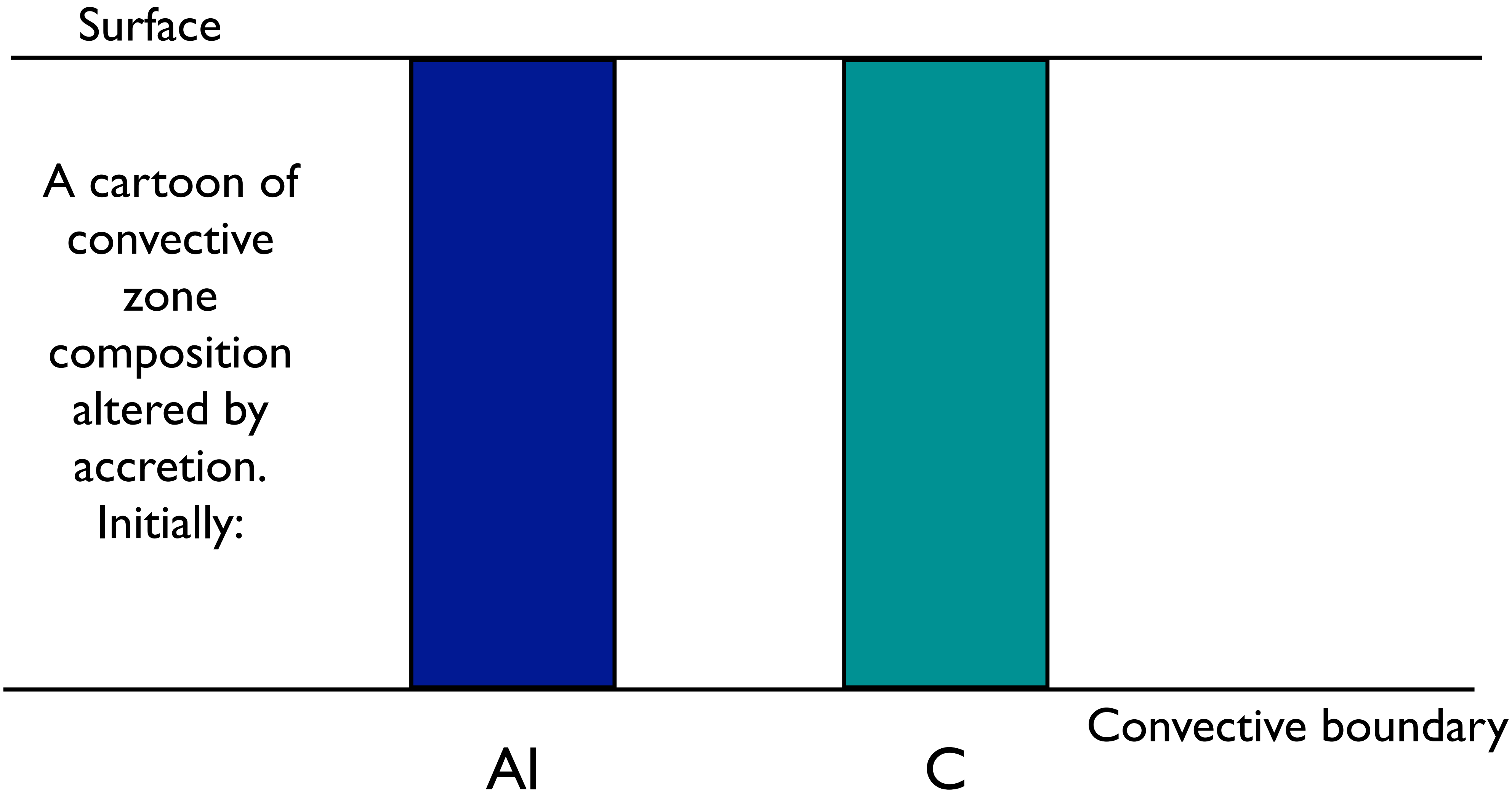
- Suggestive of disk chemistry; consistent with accretion where

$$\tau_{\mathrm{Al,Zr}}^{\mathrm{freezeout}} < \tau_{\mathrm{Fe}}^{\mathrm{freezeout}} < \tau_{\mathrm{CNP}}^{\mathrm{freezeout}}$$

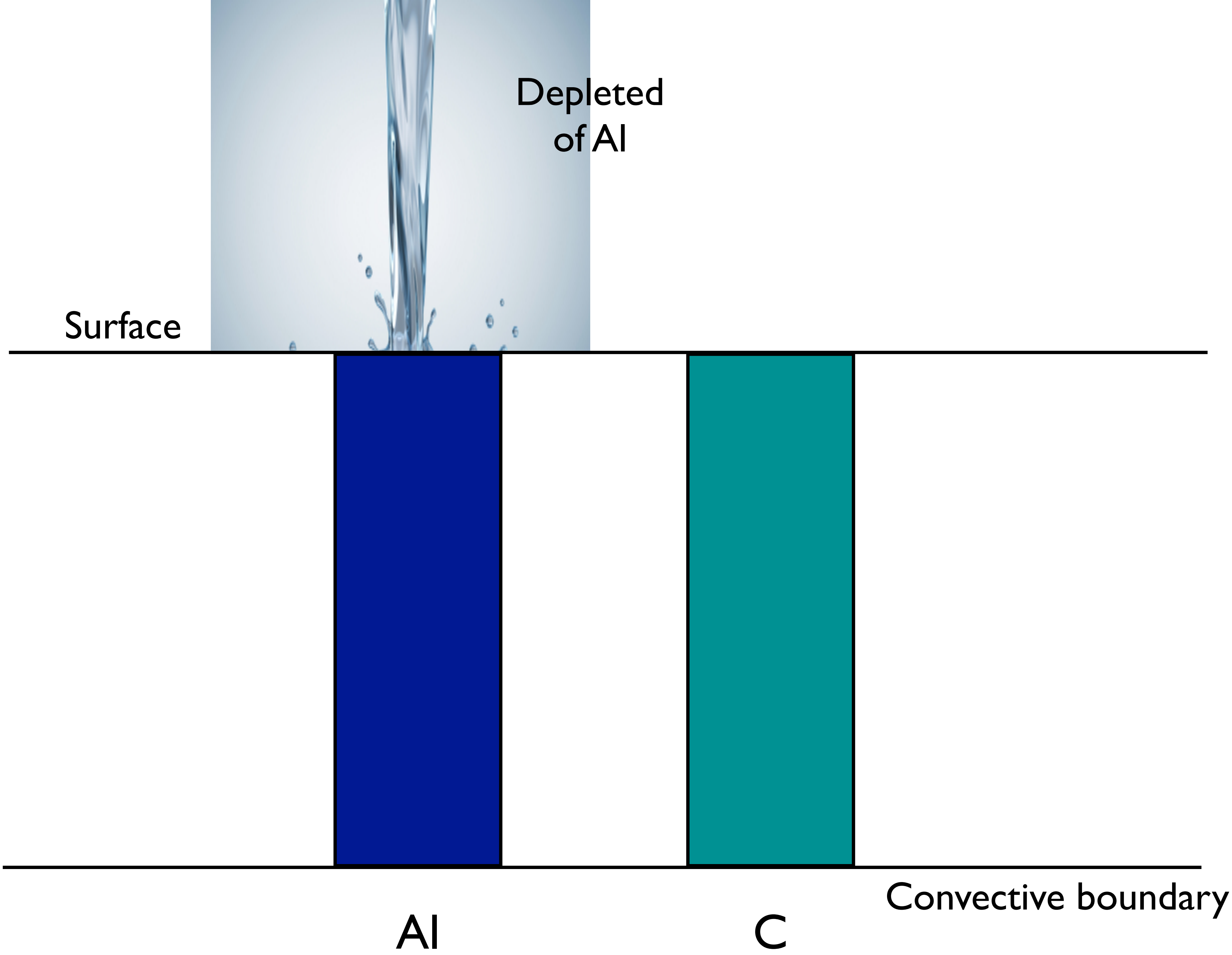
- Measurements at the limit of feasibility: debated...



# This is in accord with expectations ...



A cartoon of convective zone composition altered by accretion. Initially:



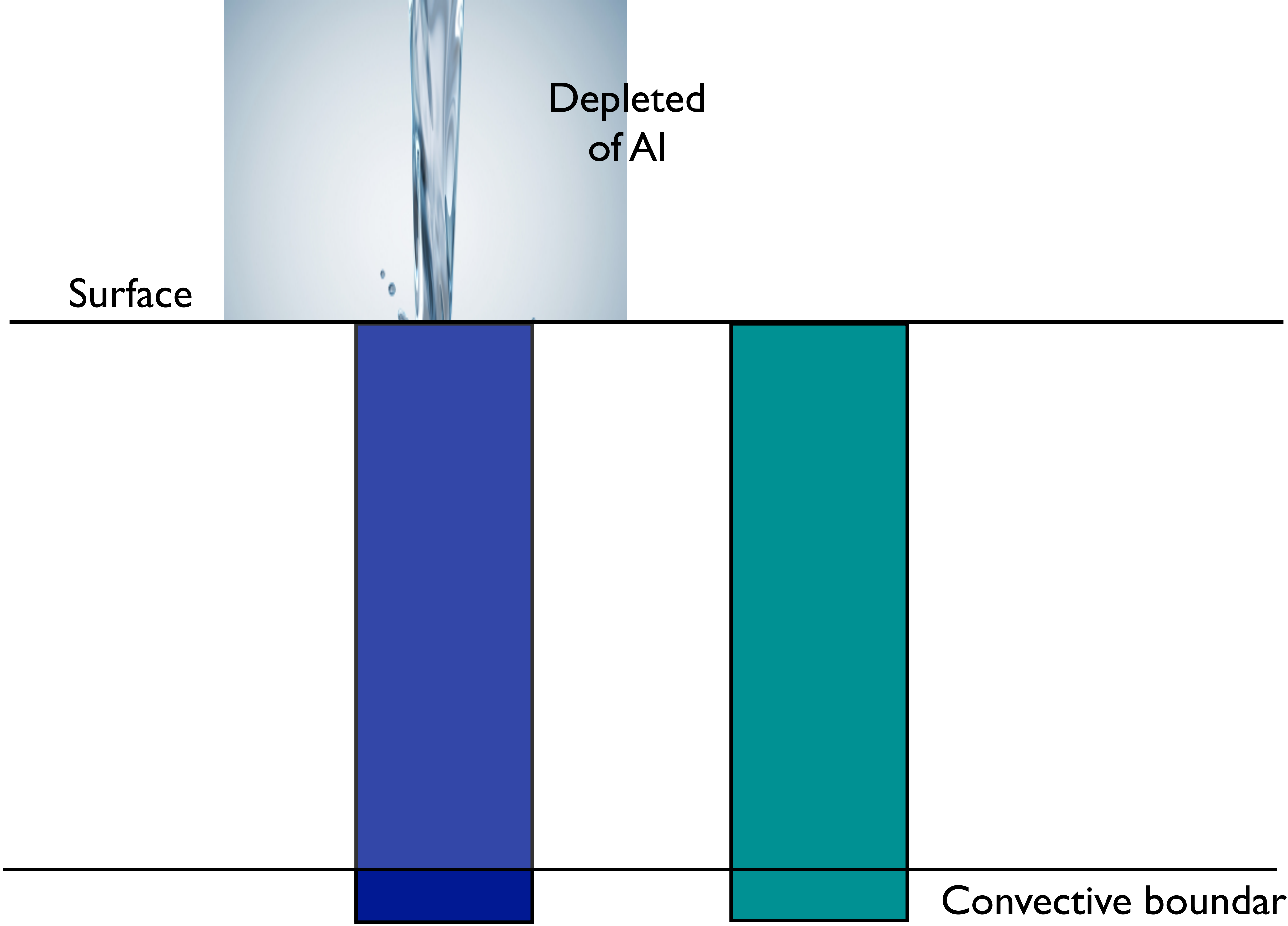
Depleted
of Al

Surface

Convective boundary

Al

C



Depleted of Al

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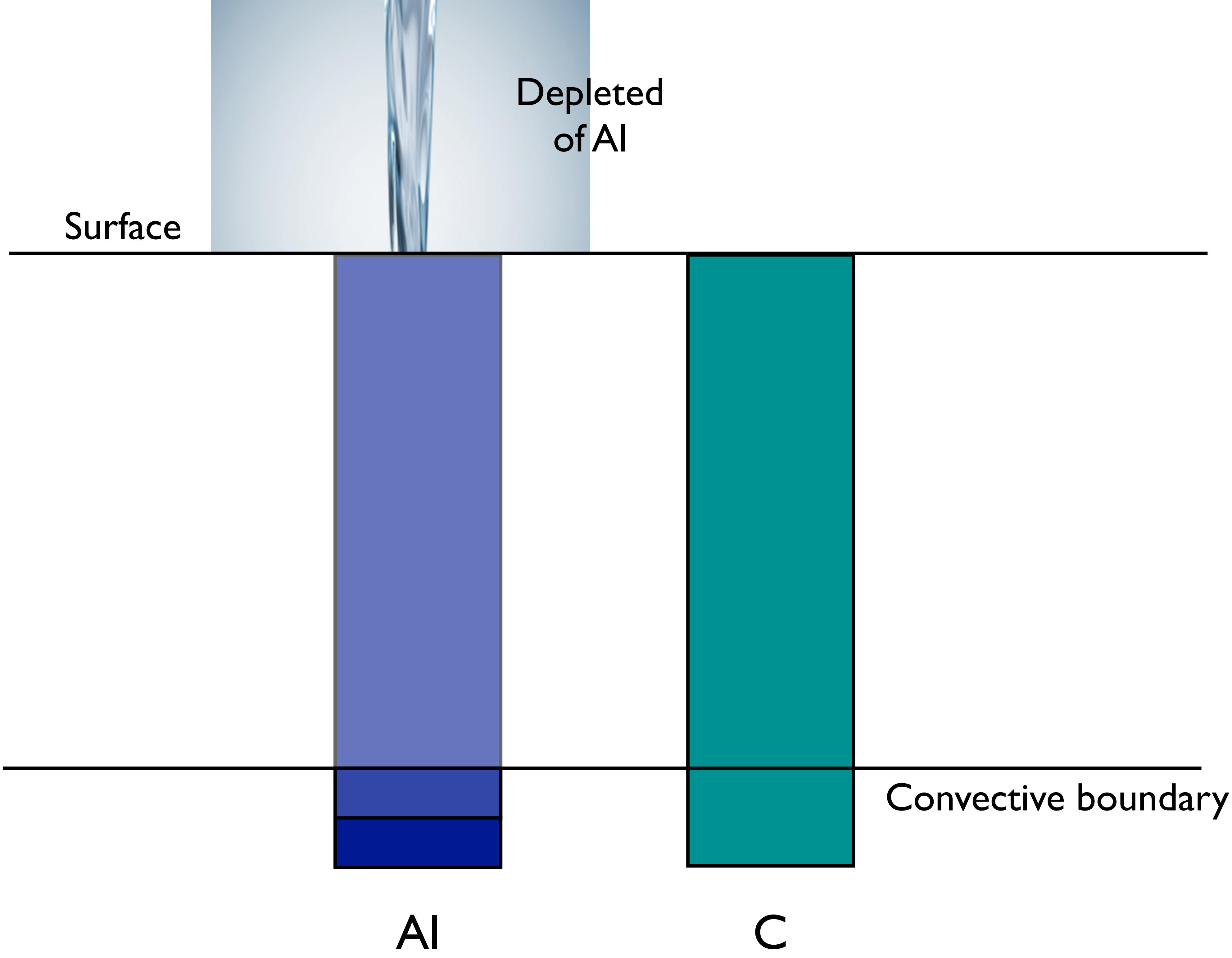
Convective boundary

Al

C



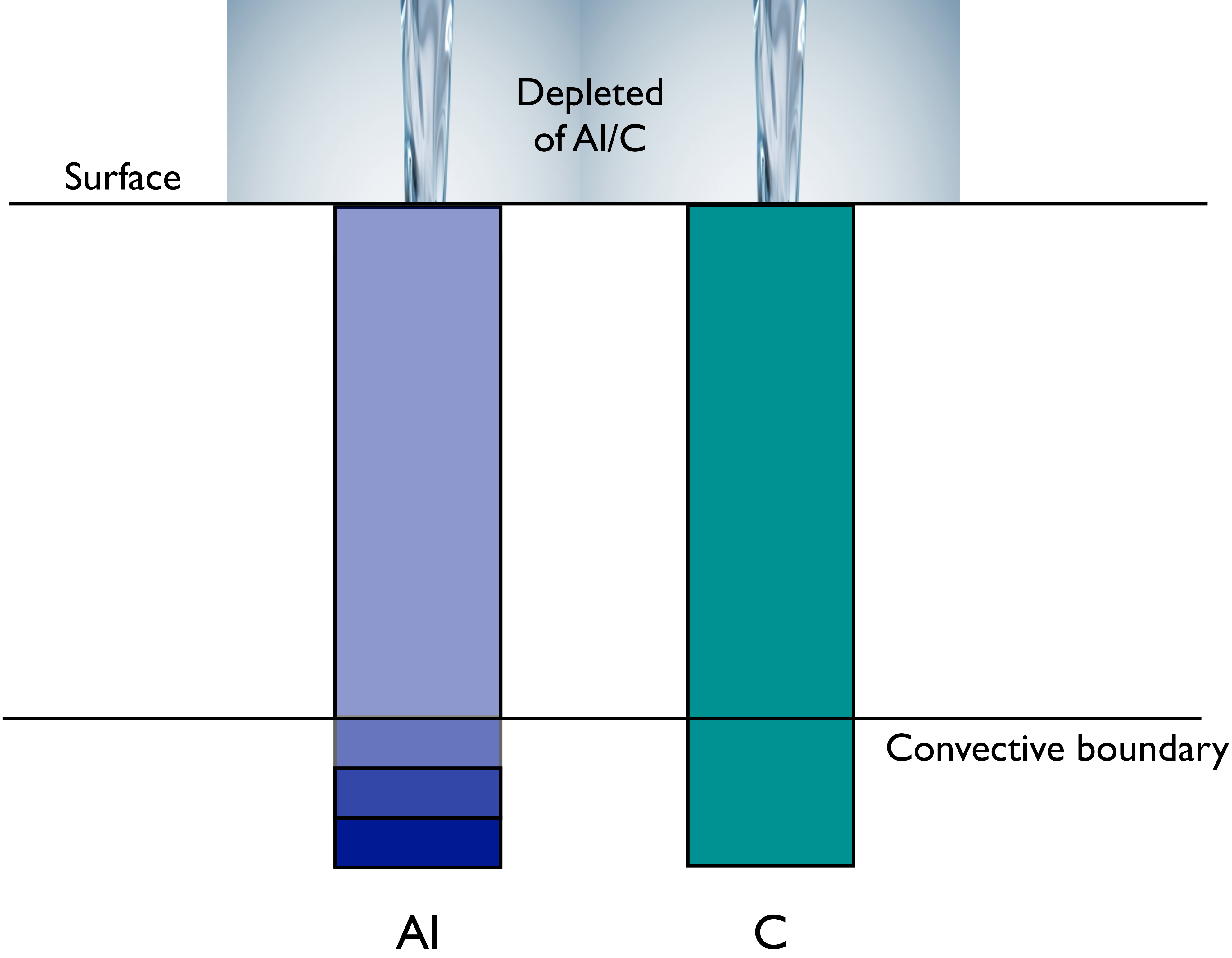
Depleted of Al

Surface

Convective boundary

Al

C



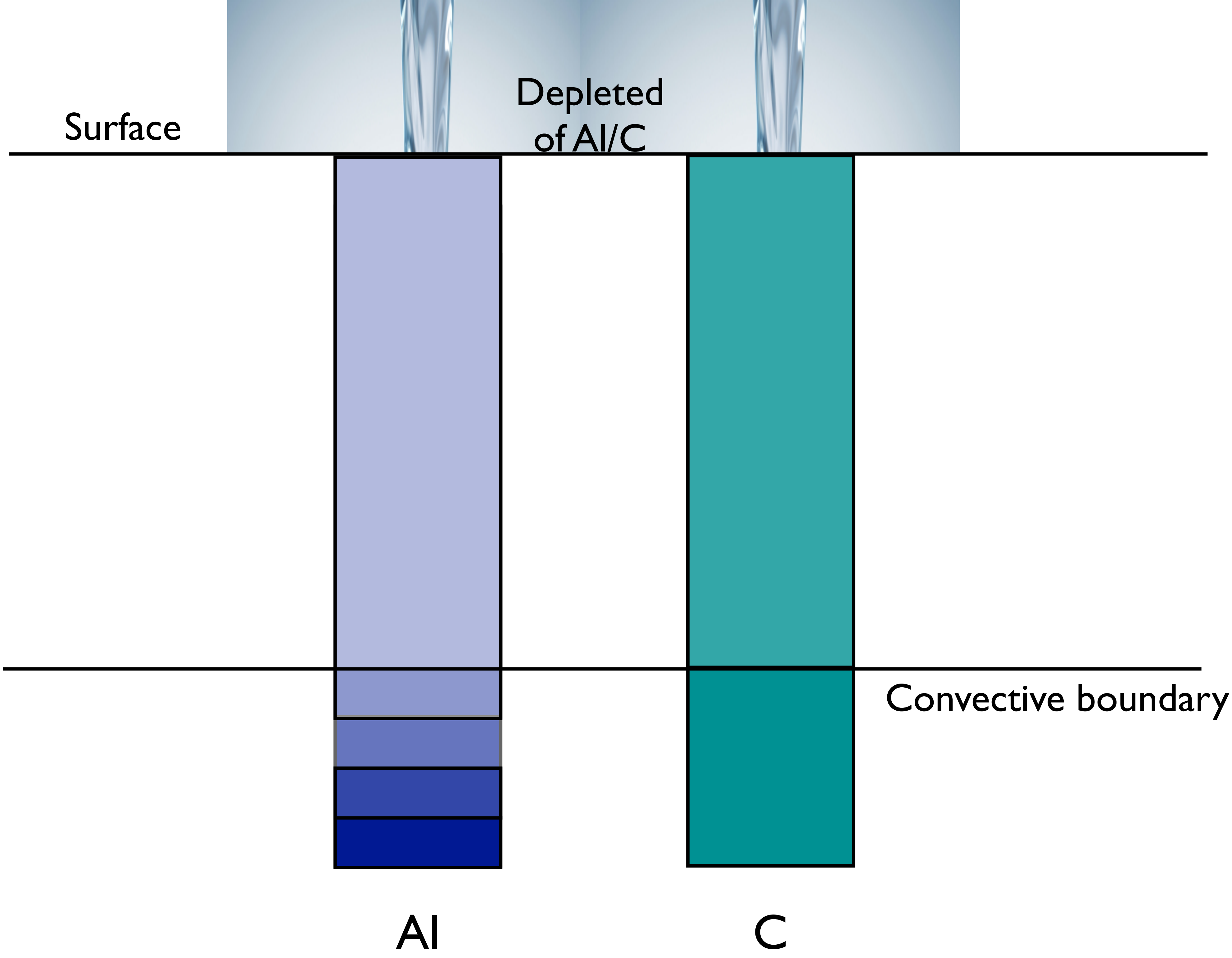
Depleted of Al/C

Surface

Convective boundary

Al

C



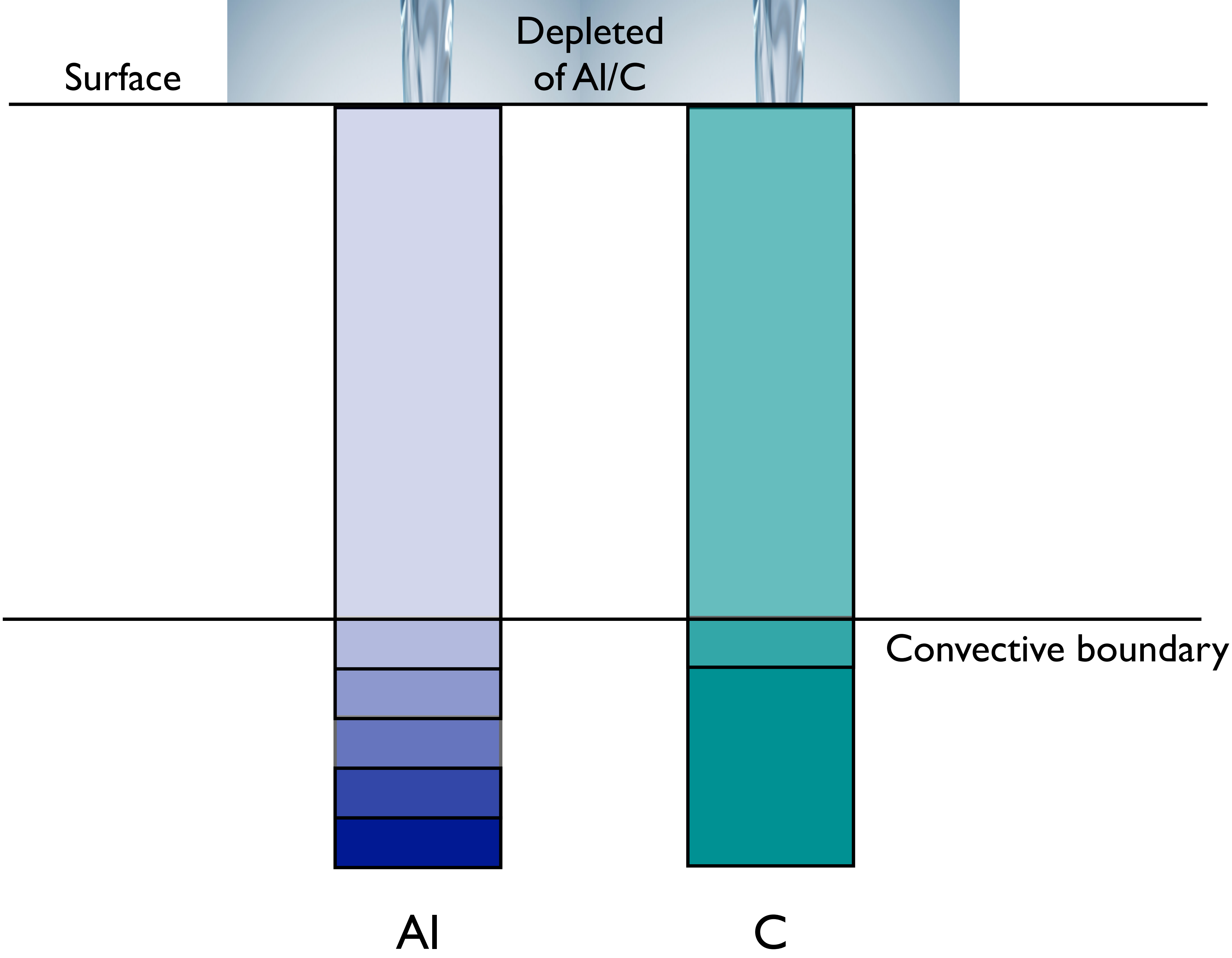
Surface

Depleted of Al/C

Convective boundary

Al

C



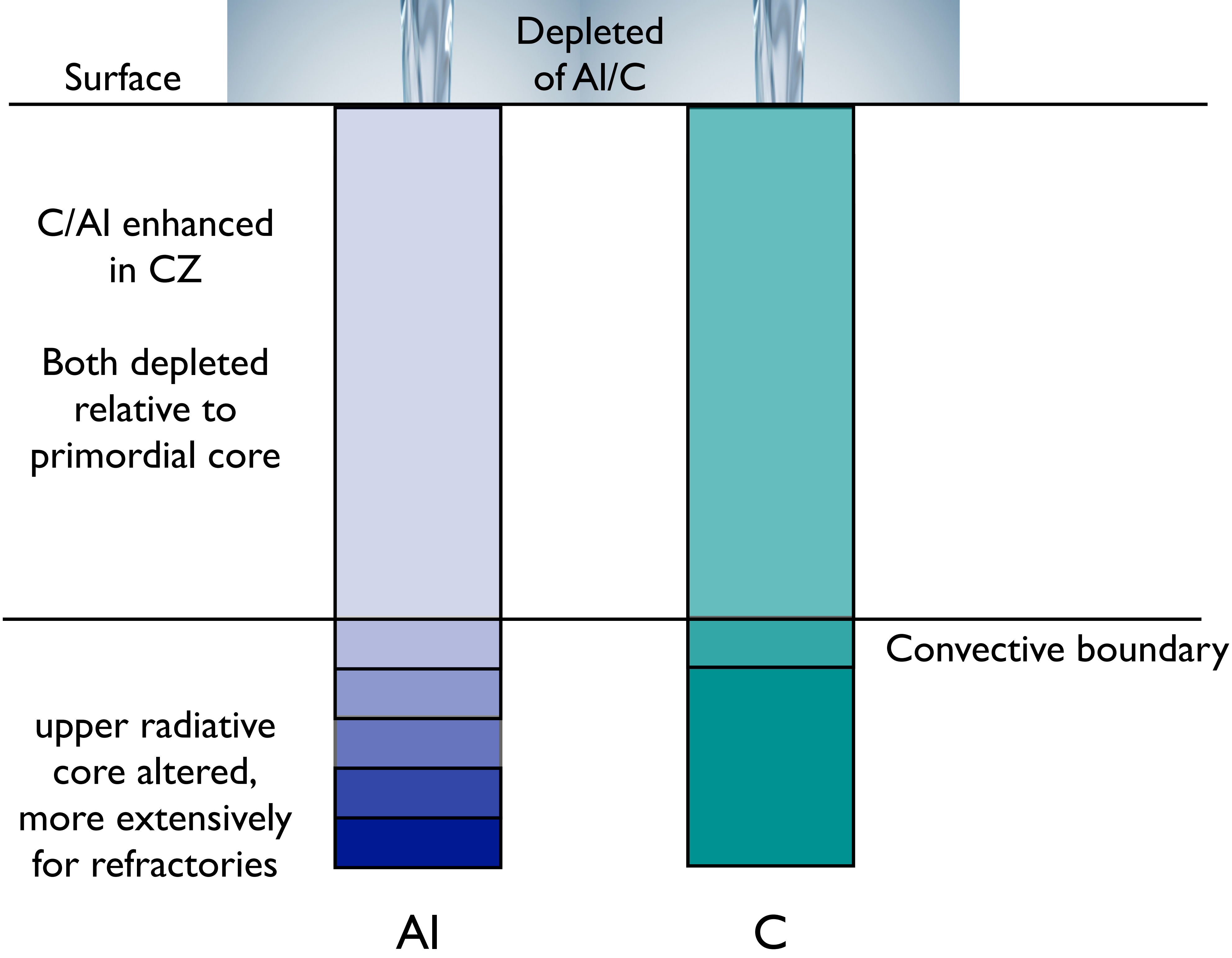
Surface

Depleted
of Al/C

Convective boundary

Al

C



Surface

Depleted of Al/C

C/Al enhanced in CZ

Both depleted relative to primordial core

Convective boundary

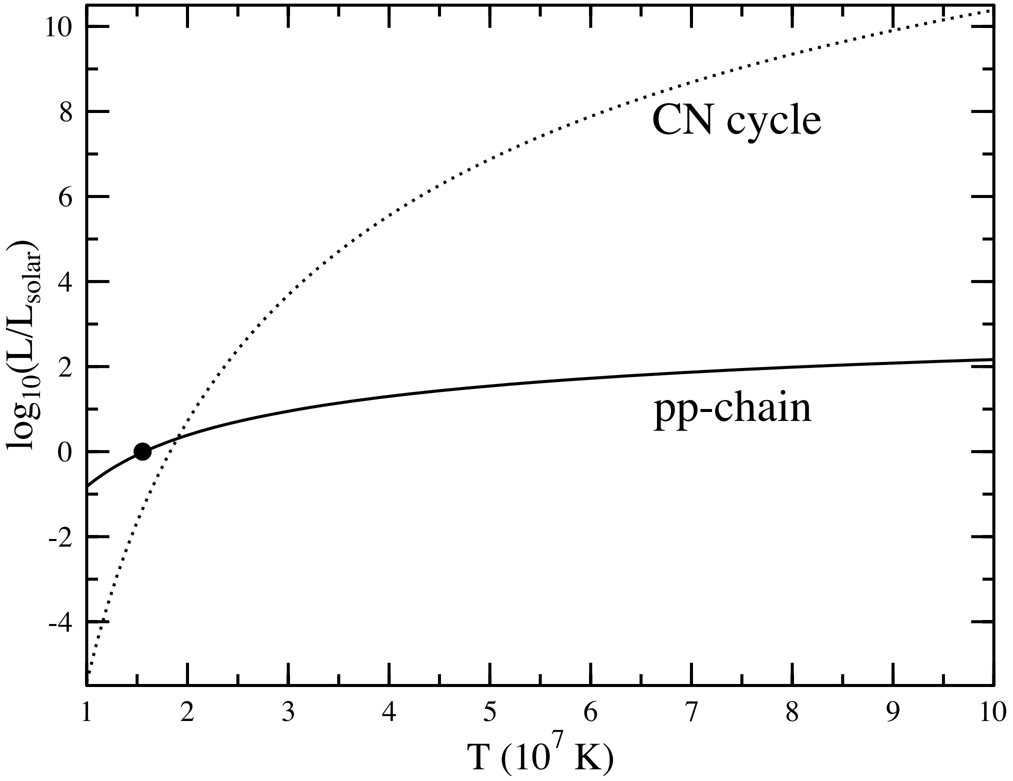
upper radiative core altered, more extensively for refractories

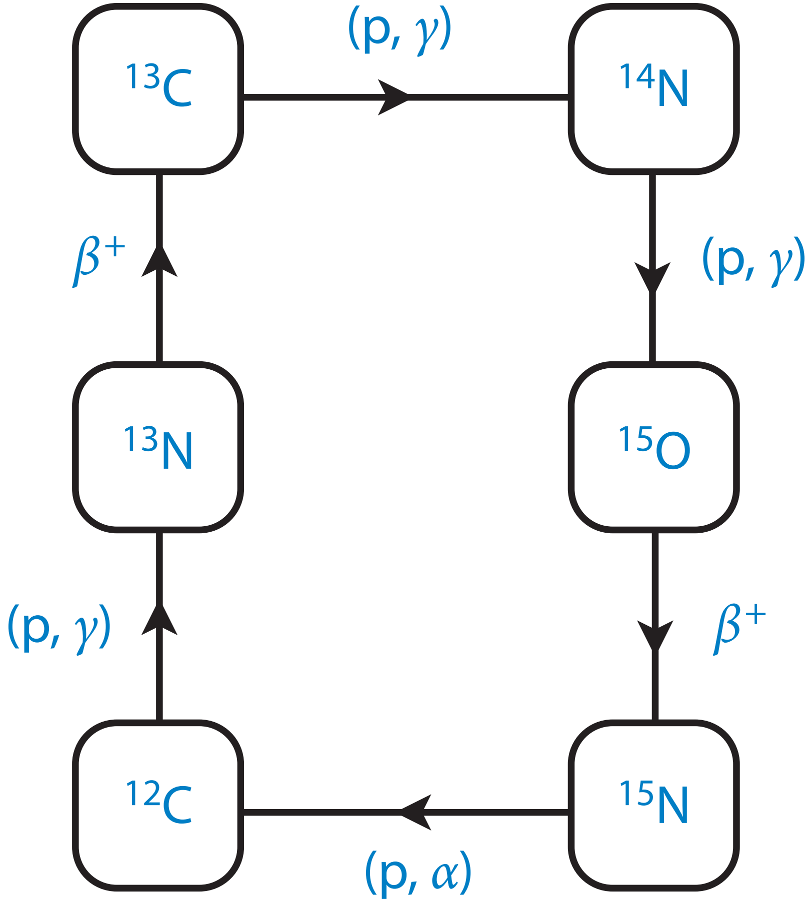
Al

C

# Using νs to Probe Solar Core Composition Directly

- ☐ pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except in the case of the first stars)





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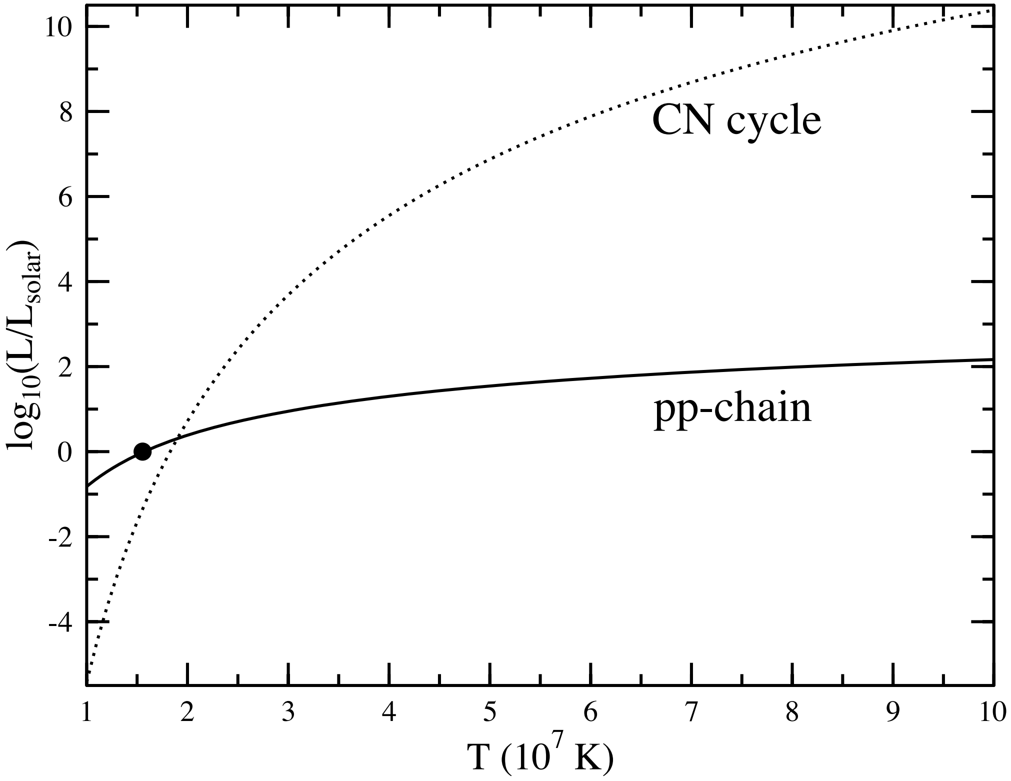

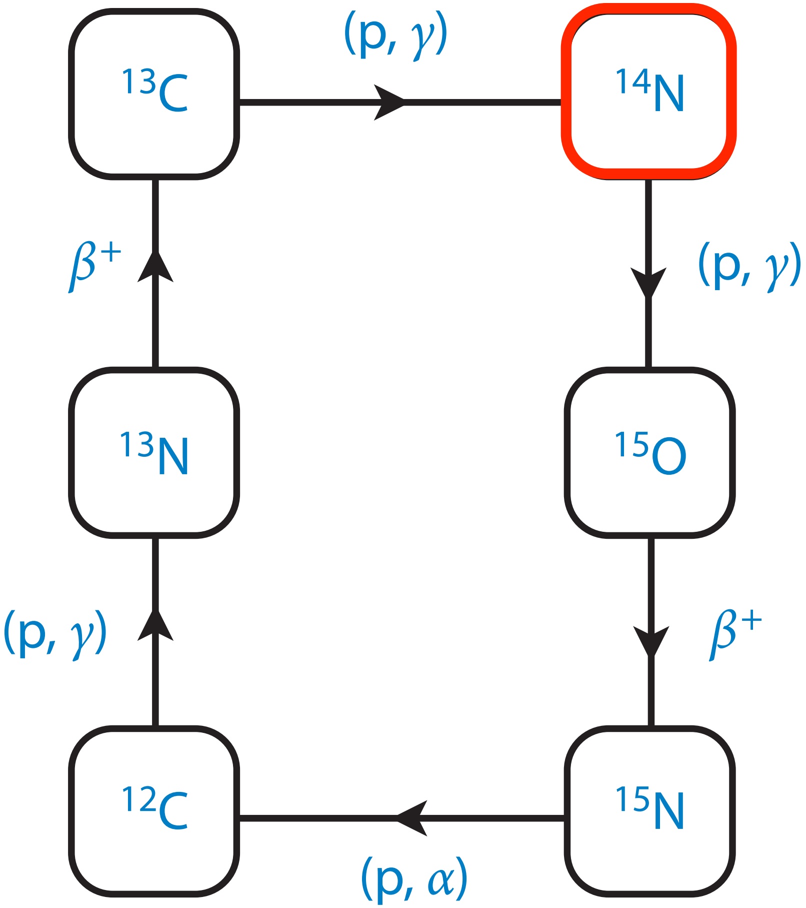

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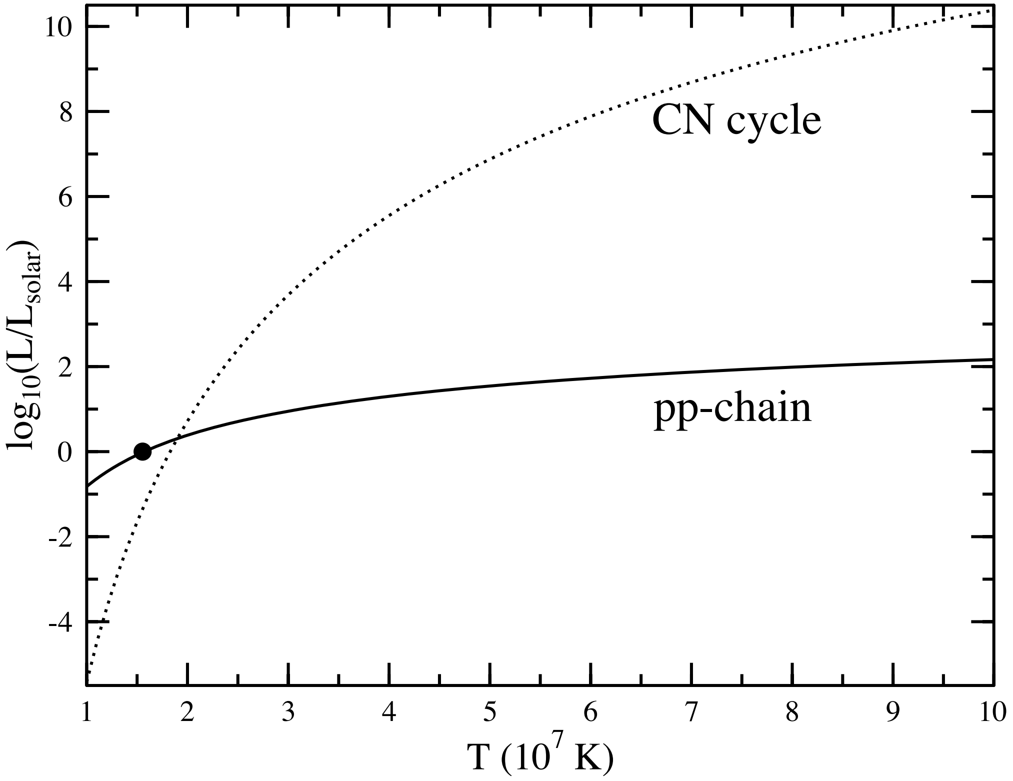
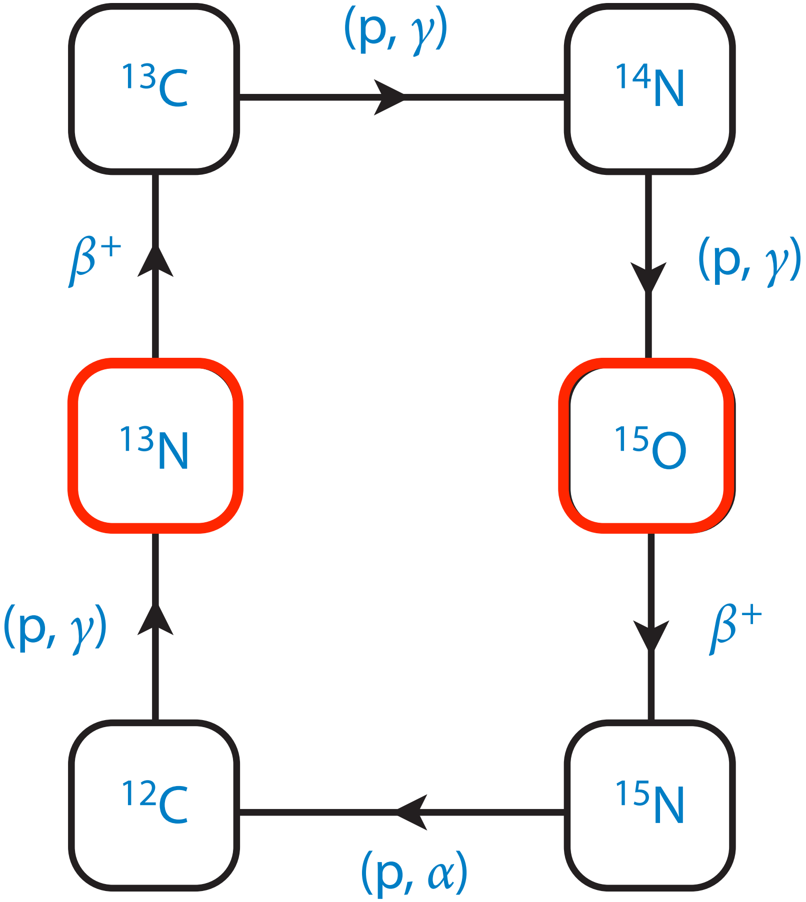
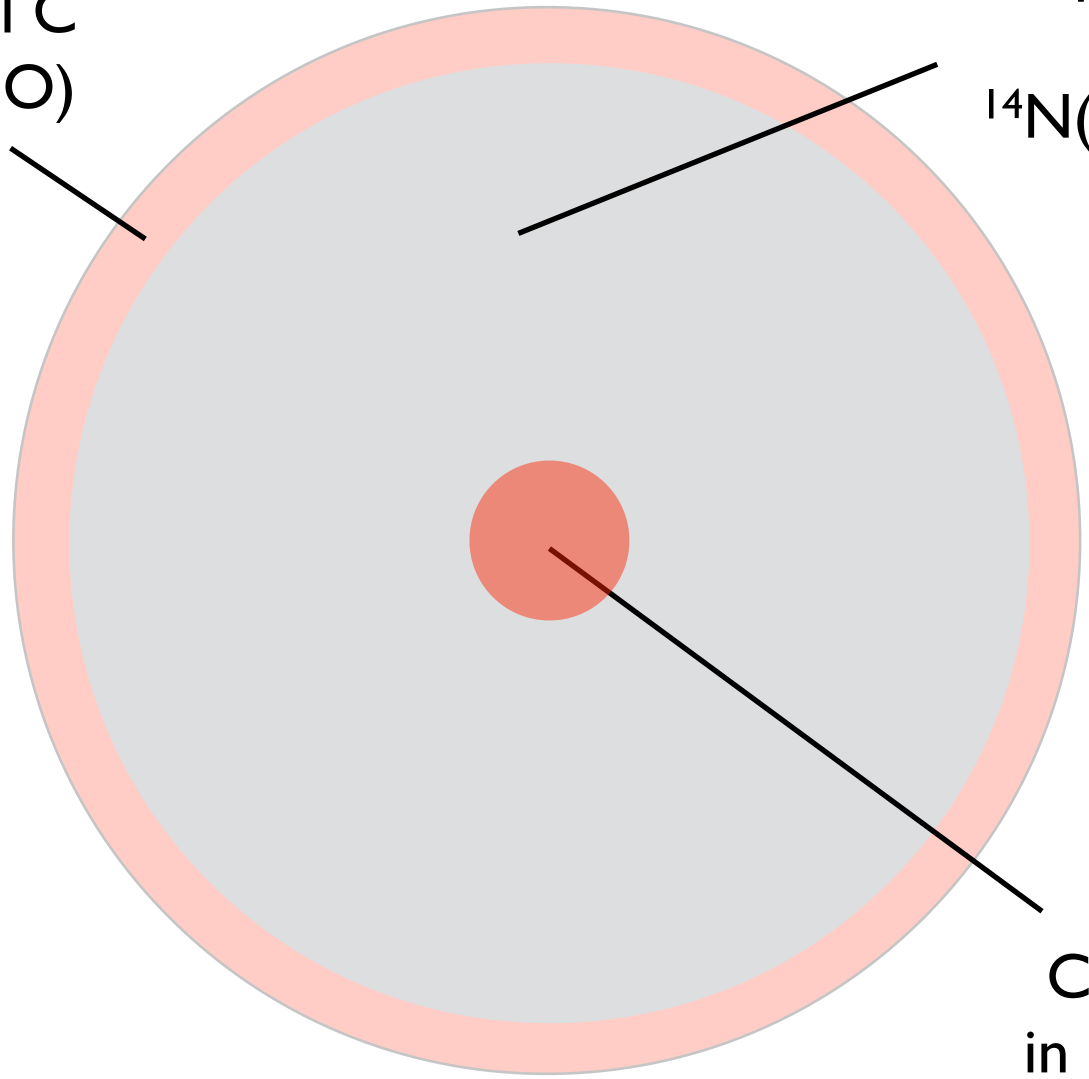




present day burning
of primordial C
$\nu(^{13}N)$ - $\nu(^{15}O)$

primordial C
burned:
$^{14}N(p, \gamma)$ bottleneck



CN burning
in equilibrium
@ $T_7 \sim 1.5$
$\nu(^{13}N)+\nu(^{15}O)$

solar core

❑ measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \;\; E_\nu \lesssim 1.199 \text{ MeV} \;\; \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \;\; E_\nu \lesssim 1.732 \text{ MeV} \;\; \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

❑ these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on the total core C+N

❑ absolute fluxes are uncertain, sensitive to small changes in many solar model uncertainties other than total metallicity

❑ but an appropriate ratio of the CN and $^8$B ν flux is independent of these other uncertainties: the measured $^8$B ν flux can be exploited as a solar thermometer

# the bottom line

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

measured to 2% by SuperKamiokande
(the solar thermometer)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

what we want to know: the primordial core abundance of C + N (in units of SSM best value)

$$\frac{\phi({}^{15}\mathrm{O})}{\phi({}^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi({}^{8}\mathrm{B})}{\phi({}^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} \quad x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \underbrace{\pm\, 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D})} \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

the entire solar model dependence: luminosity, metalicity, solar age, etc., eliminated -- except for small residual differential effects of heavy element diffusion (necessary to relate today's neutrino measurements to core abundance 4.7 b.y. ago)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times \left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

$$\uparrow$$

we have some work to do here: $^{7}\mathrm{Be}(\mathrm{p},\gamma)$, $^{14}\mathrm{N}(\mathrm{p},\gamma)$

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

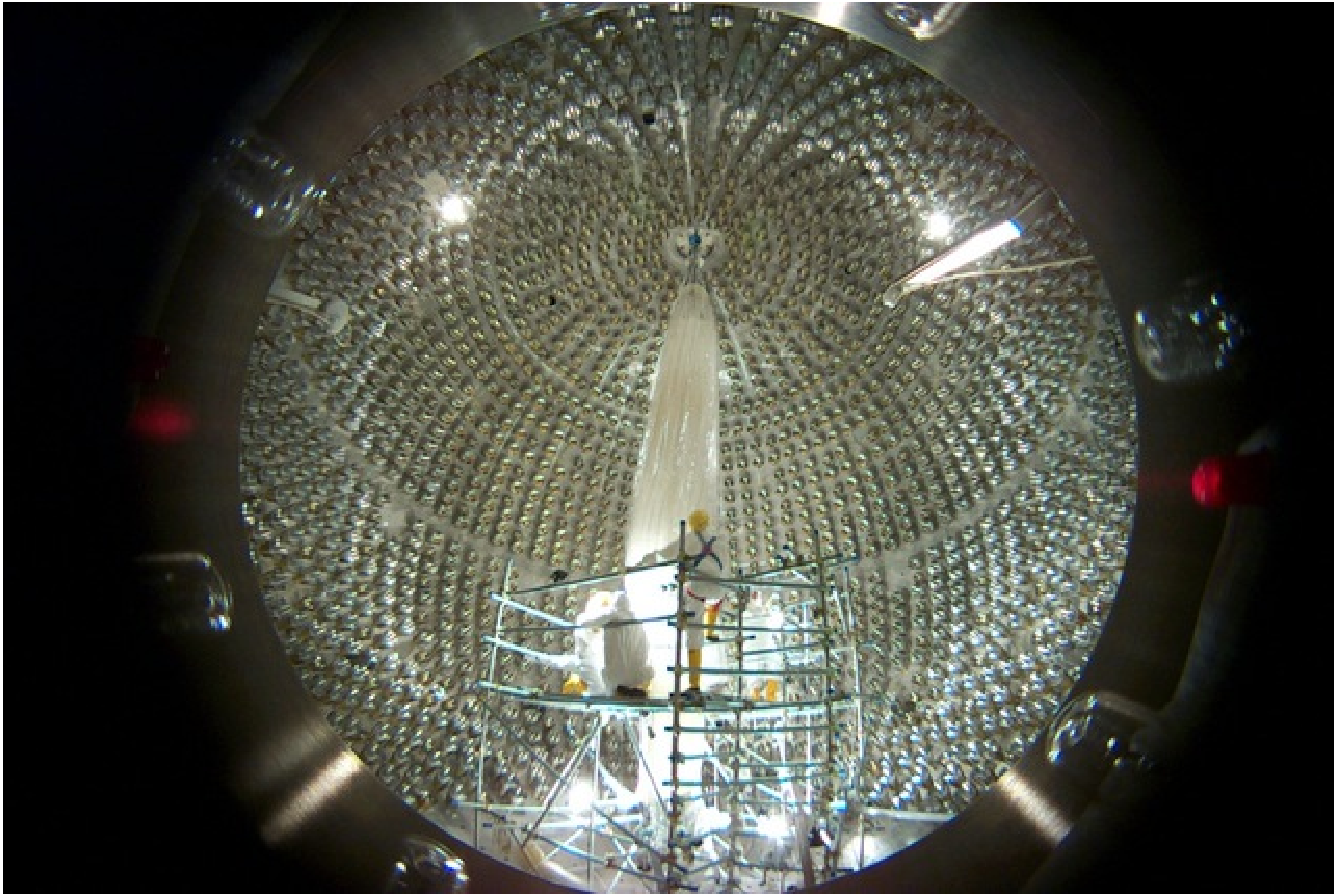
↑

SNO's marvelous measurement
of the weak mixing angle

a future neutrino measurement: Borexino, SNO+, JinPing....?

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

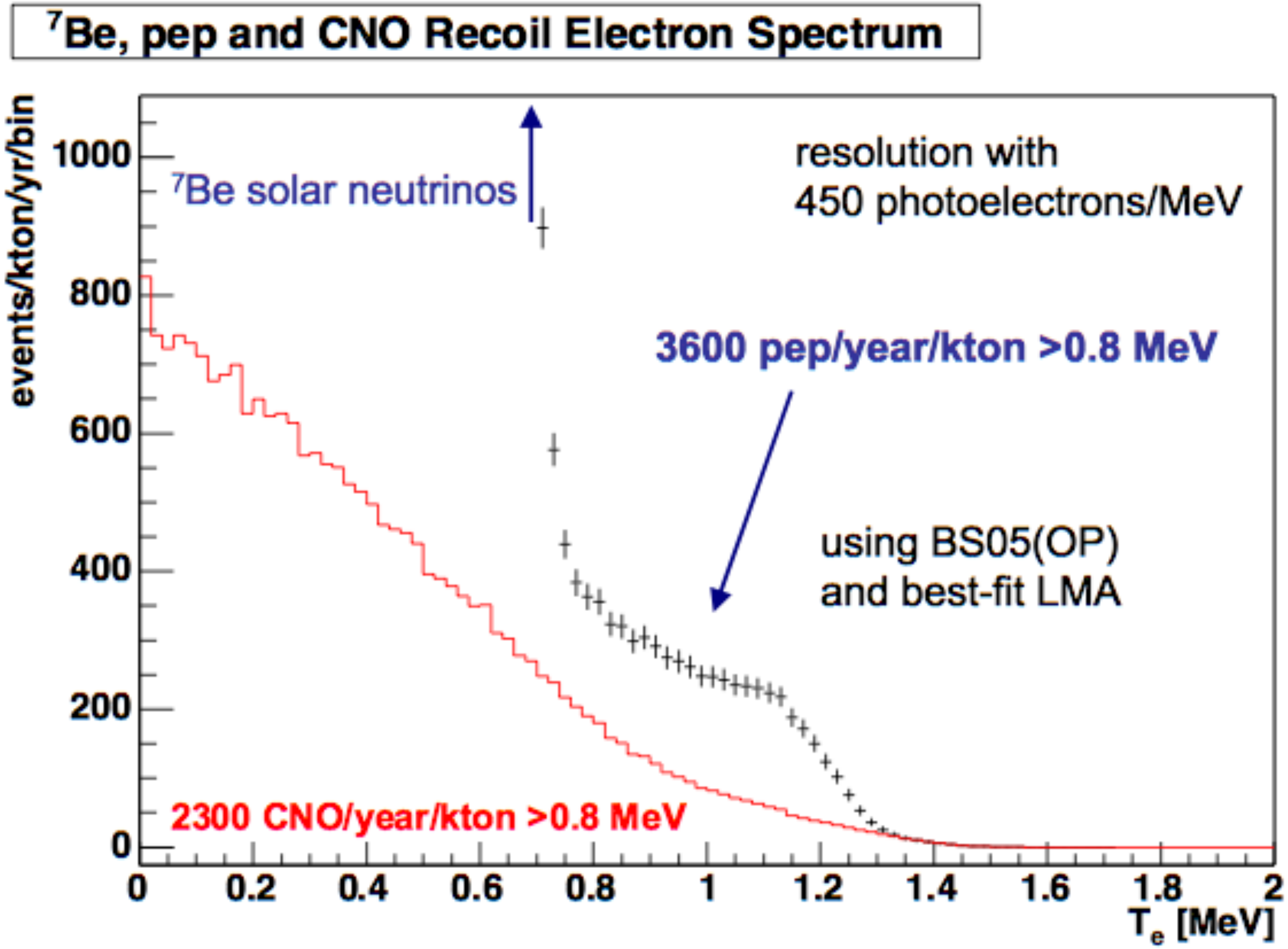
$$\times \left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$



Both SNO+ and Borexino have considered such a measurement

Depth crucial: SNO+/Borexino $^{11}C$ ratio is 1/70

# an obvious candidate for exploiting JinPing's depth



(from Mark Chen)

this measurement is fundamental

❑ probes the primordial gas from which our solar system formed

❑ the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions

❑ could help motivate "standard solar system models" that would link solar $\nu$ physics, solar system formation, planetary astrochemistry

# summary

1960s

test the solar model: precise determination of core temperature

→

1990s

new neutrino physics: precise weak interaction parameters

→

2020

CN $\nu$s, primordial metallicity, solar system formation

Now that we have eliminated the weak interaction uncertainties that held us back for many years, we can finally use solar neutrinos as a precise probe of solar physics